OCCULTATION OBSERVATION METHODS

A Thesis

Michael D. Carroll

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by

Michael Dale Carroll, B. Sc.
Lieutenant, United States Navy

The Ohio State University
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Approved by

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Adviser
Department of Geodetic Science

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CHAPTER 1

INTRODUCTION

The determination of distances and directions between points or, what is equivalent, the determination of the geodetic coordinates of the points is a long and arduous job when the points are widely separated. Stations may be located by the classical geodetic methods of triangulation or trilateration in a series of steps involving the repetitious measurement of many angles and/or distances. There are, however, many disadvantages to this classical method when the stations are separated by long distances. The amount of time and money involved to construct and observe the intermediate stations is tremendous. Furthermore, the propagation of error over these long distances seriously affects the accuracy of the final position. There are, in addition, circumstances where construction of the intermeadiate stations is impossible. When the stations are separated by impassable country or by a wide expanse of sea, some other method than triangulation or traverse must by used.

There are available to the geodesist today three methods

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which could be used to resolve this problem and give a precise geodetic position of a point on the earth. These methods are: Satellite observations; Astro-gravimetric observations; and eclipse and occultation observations.

Several methods of satellite observations are currently used which can give geodetic positions. They are grouped into optical and non-optical methods. The optical methods make use of photographic plates of the satellite's path across the stellar background. The data obtained from photogrammetric reduction of the plates is analyzed and the position of the satellite at an instant of time can be determined. Through geometric or orbital analysis of the satellite's position, the coordinates of the observer may be obtained. The non-optical methods involve a combination of electronic aids, either in the satellite or on the ground, which give data that will give the ground position of the observer, in relation to the position of the satellite. The precision of the satellite methods is currently estimated to give positions to $\pm$ 10 meters.

The principle of the astro-gravimetric determination of position is that an astronomic position can be corrected for deflection of the vertical, due to the gravity field, to obtain the absolute geodetic position. A gravity survey of the area surrounding the observation site must be conducted in order to compute the gravity field.

This survey is extremely laborious and the resultant accuracy of computation of the deflection of the vertical is dependent on the knowledge of the gravity anomalies for the entire surface of the earth. Highest accuracy is required, since an error of 0."3 in deflection of the vertical corresponds to about 10 meters in position. It has been estimated by Hirvonen that the rms error in the values for deflection of the vertical in the United States and Central Europe would at best be ± 0."85[Hirvonen, 1956]. Errors in areas which have not been as extensively surveyed would greatly exceed this. Kaula has published a graph of the error in gravimetrically determined deflections of the vertical with perfect knowledge of the gravity out to given radii [Kaula, 1957]. This is reproduced as Figure (1). Because the gravity anomalies of the whole earth are not known very accurately, this method is not currently used for general position determination. Only a few selected stations have been computed.

The relative infrequency of eclipses and their restricted path of visability precludes their use in geodesy in other than special circumstances. Occultations, however, occur every night and can be used for geodetic purposes over most of the earth. In general terms, the theory of the occultation method lies in the fact that the apparent daily motion of the moon across the sky in

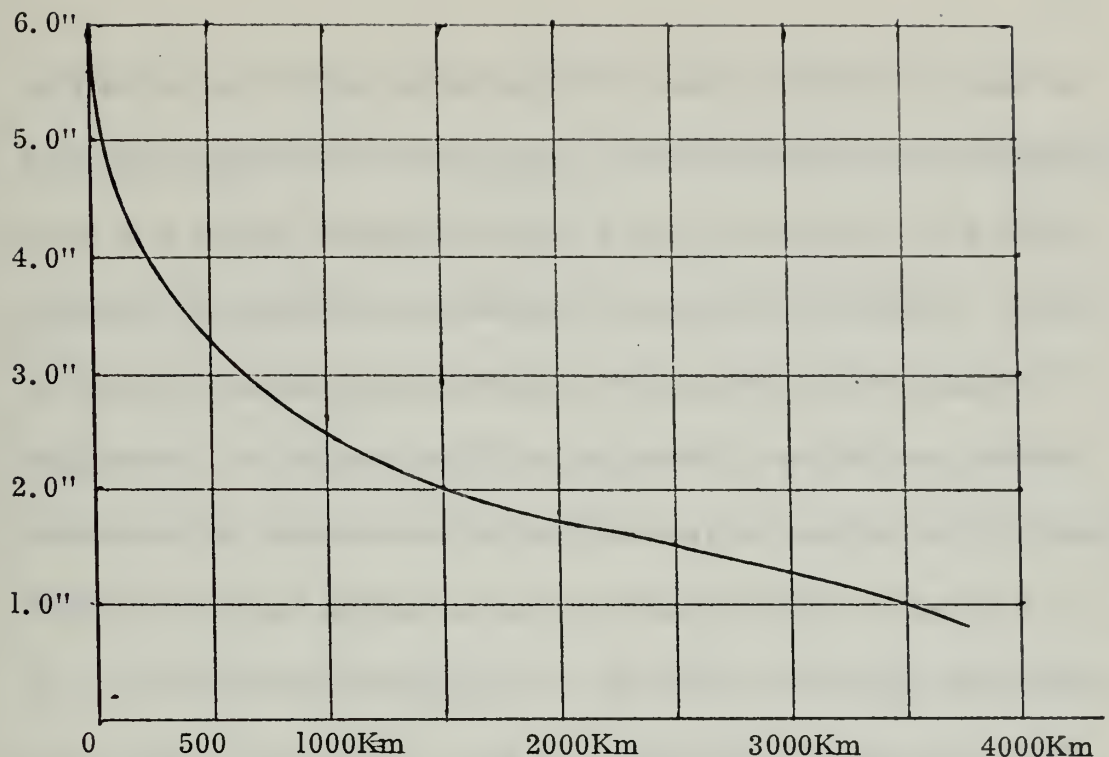

Figure 1. - Rms error in gravimetrically computed deflections of the vertical with perfect knowledge of gravity out to given radii. [Kaula,1957]

relation to the stellar background will cause the moon to pass in front of and hide stars in its path. As the moon has no atmosphere, there is a sudden disappearance of a star in its way. This disappearance is called the occultation of the star by the moon. After an interval, as the moon continues its relative motion, the star reappears. To locate a point on the earth's surface, we merely determine the exact instant at which a star is occulted at this point. There is obtained at that instant, a definite relation between the star, the moon and the observer. Since the occultation takes place at the edge of the moon, to fix this relationship requires not only the location of the star and the center of the moon, but requires the direction and distance from the center to the edge of the moon at which the star was occulted. The determination of this direction and the lunar radius at the point of occultation can be accomplished by either of two methods of reducing the occultation observations, either one of which can give acceptable results. Since the cessation of the Army Map Service occultation observation program in the late 1950's, there has been no routine program of recording occultations for geodetic purposes. Only random observations have been made and mostly for non-geodetic purposes.

This thesis is concerned with the procedures used to observe and record occultations. The considerations underlying the

computations that must be done before the occultation, as well as the final reduction procedures, are introduced for background. The theory and mathematical procedures for the methods of obtaining a position by observing occultations is well documented in most of the references listed in the bibliography. The reader is directed particularly to [Mueller, 1964] and [Henriksen, 1962] if a thorough understanding of the reduction of the data is desired. Mathematical procedures and sample calculations can be found in [St. Clair, 1964].

The original plan for this thesis was to erect an occultation telescope which had been loaned to the Ohio State University, by the Army Map Service, and through a series of occultation observations establish a position. Then, by comparision of the coordinates with known geodetic coordinate, an estimate of the errors of the occultation method could be made. This was to be an extension of St. Clair's work, as he was unable to observe occultations to establish a position. However, this observer also was unable to record any occultations with the photocell and the work soon concentrated on analysis of the instruments and the procedures for their use in the field.

It was desired that this thesis be of such a format that it could be used as a "Manual of Procedures" to assist geodesists in conducting an occultation observation program with this type of

instrument. The assumption has been made that the reader will be fimiliar with the basic principles and terminology of geodetic astronomy.

CHAPTER 2

PRELIMINARY COMPUTATIONS

2.1 General Planning

It must be assumed that a need has been generated for determining the geodetic coordinates of some point on the earth's surface. As mentioned in the preceding chapter, the classical methods of triangulation might not always be the best procedure to use, in fact, in many locations it may be impossible to use. The observer will have evaluated the location in which a position is desired and decided on which of the position determining methods would best be suited for this area. If the occultation method was selected, this chapter may be followed to assist the geodesist in planning the task.

The first step in the planning of the mission would necessarily be the determination of what stars will be occulted at the given place and their approximate times. It must also be decided as to whether the Single-Site-Method or the Equal-Limb-line-Method will be used. The Single-Site method requires the observation of occlutations to be over as great a range of position angles as possible. The geodetic unknowns and as many of the astronomicical

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unknowns as possible, are solved by the method of least squares. The variations in the radius of the moon at the point of occultation are reduced to a minimum by applying a correction for the height of the occulting topographic feature using the charts of Dr. Watts [Watts, 1963]. These charts can be considered accurate to 0.07" [Mueller, 1964]. It is expected that the residual variations will act in the solution as if they were randomly distributed in the many occultations observed and, hence, will not appear in the values found for the geodetic unknowns.

The Equal-Limb-Line method removes the uncertainty in the radius of the moon by using a second observer to determine the radius for the same occultation as that viewed by the first observer. Since no reliance is placed on statistics to produce results, the accuracy of this method is inherently greater than that of the Single-Site method. This method utilizes the second point as a "control point" and its geodetic positions must be known.

The Single-Site method can be utilized with satisfactory results if enough observations are made. The random errors in the limb corrections will cancel and only the small systematic errors from the method of determining the corrections will remain. The Equal-Limb method eliminates this problem, but for a given occultation the location of the "control point" on the equal limb line, or in other words, the position of a point that will see the occultation at the

same selenographic latitude, will be unique from that of other occultations. The weather conditions must permit observations at both stations, otherwise the method can not be used. The probability of two sites being on the equal limb line of more than one occultation is very remote. As a minimum of two separate pairs of observations must be made to fix the position of the unknown station, it must be anticipated that the observation team at the control point is going to have to move to several locations, or more observation teams will be required.

After the tentative locations of the sites are determined, the prediction procedures are used and approximate time of occultation is computed. Using the approximate times, the equal-limb-line is determined and the location of the "control points" selected. Once the sites have been occupied and the best available coordinates are reported, the computation of the exact time of occultation for these coordinates will be made.

2.2 The Prediction of an Occultation

Since 1960 the American Ephemeris and Nautical Almanac has not published any information on the circumstances of occultations. However, H. M. Nautical Almanac Office continues to make predictions of occultations for 88 central stations and publishes them with latitude and longitude coefficients to enable observers

near these stations to compute times for their own location. This data can be found in several periodicals including "Sky and Telescope" (Sky Publishing Company, Harvard College, Cambridge, Massachusetts). This data is easily interpolated to give the stars and dates of occultations that may be seen from a general location. The time can be determined by using the latitude and longitude factors in the method explained in the tables. By special arrangement with H. M. Nautical Almanac Office, they will provide a machine-printed table of occultation predictions for a specific location. A letter request to the Nautical Almanac Office, Royal Greenwich Observatory, Hailsham, Sussex, England, stating the purpose of the occultation program and giving the latitude and longitude to the nearest minute of arc will generally be sufficent. A sample of this machine printed table for Columbus, Ohio, is included in the appendix. On this machine copy, for each occultation is the Zodiacal Catalog number, the name, the magnitude, the time of the occultation to 0. 1 minute, the elongation, the position angle on the moon's limb, and the latitude and longitude factors for the rate of change. This information listed on the machine printed tables is not given to significant accuracy to be used as the actual time prediction, but does give an excellent check on the computed values. The times can be used as the first

estimate in the computations and in general have been found to be within one second of the final predicted time.

2.3 Predicting Time of Contact

The theory and formula developement for contact prediction is presented in [Mueller, 1964] and [St. Clair, 1961]. Only the principles involved in the prediction scheme are presented here. The coordinate system used, illustrated in Figure (2), was first developed by Bessel and is defined as follows. The plane passing through the center of the earth and perpendicular to a line through the centers of the star and moon, is termed the fundamental plane. The line through the earth's center perpendicular to the fundamental plane is the Z axis, and is positive towards the star. The Y axis is defined perpendicular to Z in the plane described by the polar axis of the earth and the Z axis, positive to the north. The X axis is perpendicular to the YZ plane and is positive to the east. The coordinates of an observer are ξ, η and ζ, the coordinates of the moon's center are X, Y and Z.

To predict the time of an occultation, the geocentric coordinates of the observation point are first computed. The right ascension, declination and parallax of the moon are found from the Ephemerides at times near the predicted time of occultation. The right ascension and declination of the star are taken from the

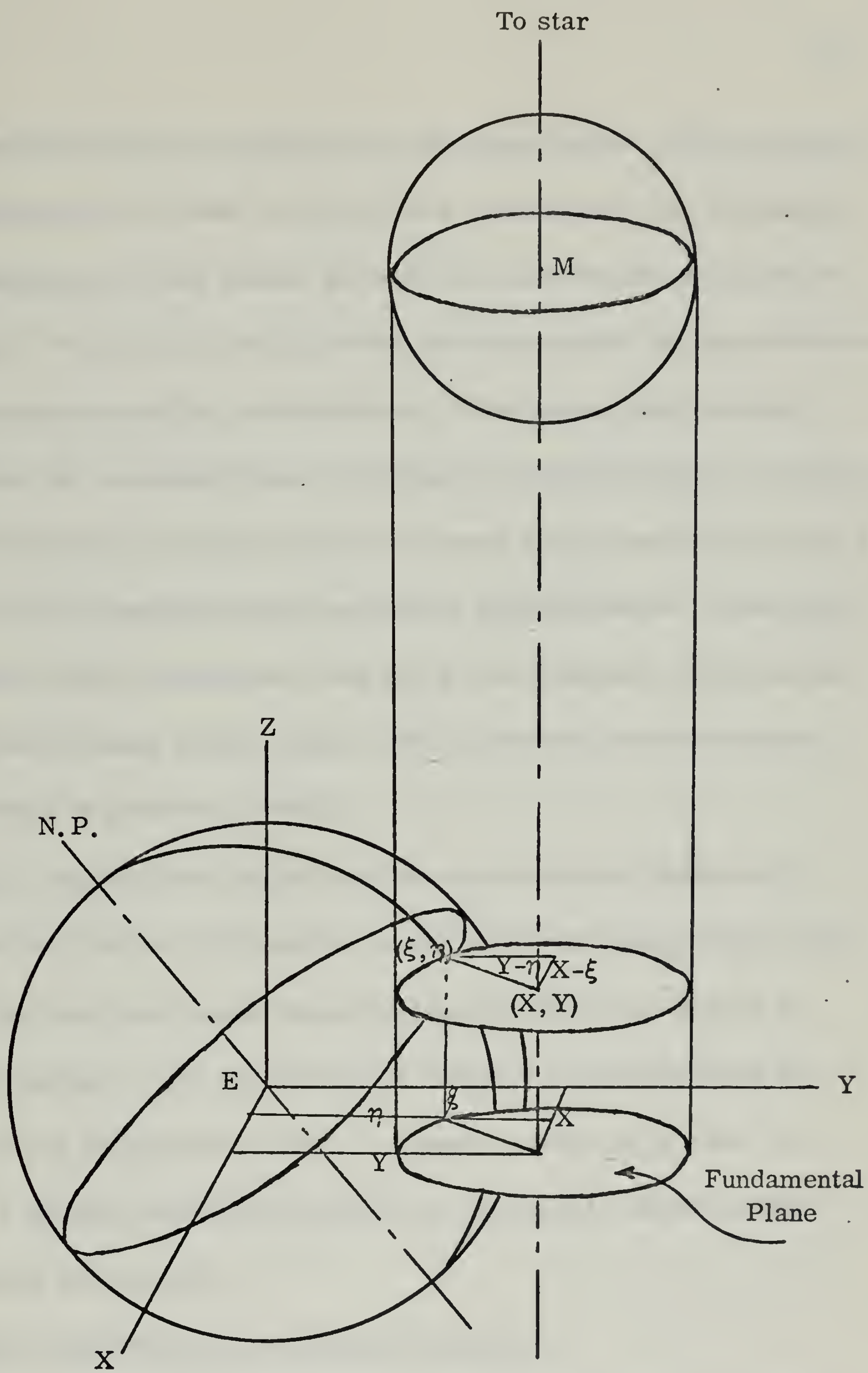

Figure 2. - Besselian Coordinate System.

appropriate catalogs and updated to the same times. The Besselian coordinates of the center of the moon's shadow are then computed for these approximate times, as well as those for the observer's position. The rate of change of the coordinates for the approximate times is determined by interpolation. The best approximation available for the actual time of contact is then used in the formulas and an iterative procedure used to correct the approximation based on the rate of change at each succesive approximation. Practical examples of this procedure, with the actual methods and formulas used, can be found in [St. Clair, 1961], some of these have been reproduced in [Mueller, 1964].

The Explanatory Supplement to the American Ephemeris contains in Chapter 10B another method of predicting contact time which has the same basic theory but approaches the solution a little differently. As the method is difficult to extract from the Explanatory Supplement without constant reference to other sections, a sample prediction problem is included in the appendix explaining the method.

2.4 The Prediction of the Equal-Limb-Line

The computations involved in determining the location of sites, all of which are on the Equal-Limb-Line, are quite lengthy.

and the method discussed here was developed by H. Hirose of the Tokyo Astronomical Observatory. For a complete understanding of the theory and formula developement the basic reference [Hirose, 1953] should be read. Mueller has, however, summarized the method very clearly and a better understanding of the principles might best be obtained by reading [Mueller, 1964] first.

There are two approaches to the problem. One is that we have a control point with the geodetic position already known, and wish to pass this control through occultation observations, to other stations; the exact location of the other stations not being the governing factor. The second approach is that we have a site for which we wish to obtain geodetic coordinates transferred by occultations from some area that a site can be constructed with geodetic control. By far the largest use of occultations will be in the second situation. We want to establish control at a previously determined site.

The method involves first the prediction of the time of contact at the site for which the position is fixed. The Besselian coordinates of a second observer on the Equal-Limb line may then be computed by holding the angle at the observer between the Y axis and the direction to the center of the shadow axis constant. The approximate time of contact for an observer in the area in which we

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wish to establish the second station is determined using the basic prediction procedures. Using this approximate time at the second station, coordinates can be determined in this area at which the occultation would be seen at the same point on the moon's limb. If we select several approximate times for the area in which we wish to locate a site, we can compute points in the area that can be used to construct a line on a map, anywhere on which we could select our site.

There are, in addition to the basic theory mentioned here, several minor corrections that must be made to the predictions. These are lunar topography, refraction of the atmosphere and height of the observer above the reference datum. These corrections will be discussed in chapter 4, as they are critical factors in the exact reduction of data to obtain a position.

CHAPTER 3

FIELD OPERATION PROCEDURES

3.1 Site Selection

The site for setting up an occultation observation station must satisfy two general sets of conditions. First of all, as discussed in the previous chapter, there are the mathematical or astronomical conditions if the Equal-Limb method of observations are to be made. The site is thus restricted to lie on a line which has been pre-computed. Consultation of available maps, aerial and ground photographs, descriptions, etc., will tentatively give a site within tolerance of these requirements. Since there are many aspects of a given area which cannot be evaluated properly from a map, the observer must use his own judgment in the choice of the site. This judgment, therefore, constitutes the second condition.

The appended check-list enumerates some of the second important considerations which should be taken into account by the observer. If the site chosen by preliminary map analysis is on private land where entry or occupancy is prohibited by the owner, if it happens to be under cultivation or is flooded at the time, if it

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is too close to a brightly lighted region, etc., the site must be moved to one offering better conditions.

Even if the pre-selected site appears perfectly satisfactory, make a map and ground reconnaissance of the area; there may be better ground a short distance away. When a site has tentatively been selected by reconnaissance, find out to whom it belongs. It is not safe to assume that what appears to be completely desolate land is ownerless or government held. Make every effort to locate the owner through county records, newspaper offices, etc., before settling on it, and obtain permission from the owner to use it. Land held by the government can usually be occupied without much formality, although notification of and permission from the responsible agency is always desirable. A verbal agreement with the owner of privately held land is usually sufficient, although where damage to crops or land by the party is possible, an informal written agreement of some sort should be obtained.

As soon as a party's area of operations has been settled, the proper authorities should be notified of the party's postal address; and when the final site is located, its coordinates and the routes to it should also be reported. The coordinates are obtained with reasonable accuracy by triangulation/trilateration from existing control in the area. If no control exists, a second order astronomic

position should be taken of the site. These coordinates will be the assumed geographic position for computation of predicted time of the occultation and to which the correction will be applied to obtain the geodetic position.

Since the erection of a telescope usually attracts a large number of curious people, especially in foreign areas, it is advisable to choose a place which is as inconspicuous as is consistent with access to motorable roads.

Check List for Site Location

1. Site ownership.
2. Permission for use of site.
3. Control points in vicinity.
4. Visibility to north and to region of occultation.
5. Stability of ground.
6. Accessibility to motor vehicles.
7. Relative elevation.
8. Radio reception.
9. Local disturbances to atmosphere (light, smoke, etc.).
10. Police notification.

3.2 Erection of the Telescope

The first task after the site of the telescope has been selected is to establish a stable base. The occultation telescope is highly compact, but like all telescopes, requires a very stable support for satisfactory work. The support should be as rigid as possible, so that alignment of the telescope will not change with varying positions. It should also be massive, so that vibrations will be damped out before reaching the telescope.

There are many different ways to provide this stable base for the telescope, but the best, when time for its construction is available, is a poured concrete platform. Plywood forms, about 3 ft x 4 ft x 1 ft, should be made which can easily be bolted together for use in the field.

Prepare the site by clearing the spot where the platform will be placed. Level the ground and remove the loose soil. It is a good practice to start the platform about 6 inches below the surface of the ground to minimize lateral movement. If necessary, dig to firm ground and fill to within 6 inches of the surface with tamped rock or gravel. The location of the bolts to attach the base plate should be clearly marked on the form and these should lie in the meridian plane. Level the form with a spirit level, pour in concrete, and trowel the surface smooth.

When materials are not available or the time does not allow for the construction of the concrete platform, the base plate may be placed directly on the ground. Care must be taken to remove the loose soil and the ground tamped very firm and level. If this method must be used, 18 inch metal stakes should be driven well into the ground at an angle through the bolt holes in the base plate. Satisfactory results may be obtained using this method if the ground is not too soft.

After the base plate is secured the pedestal should be attached to it. This is accomplished by one bolt in the center of the north foot and two clamps on the south corners. In the center of the south foot is a slot through which must extend a small vertical plate from the base plate. Against this vertical plate a push-pull arrangement of horizontal screws on the pedestal will be used later for polar alignment.

Next, the right ascension assembly should be attached to the stand. There are four bolts which hold the assembly to the top of the stand. Care must be taken during this and all subsequent operations to be careful of balance of the components. One man must hold the right ascension assembly in a horizontal position while another man secures the bolts. The components as now assembled are heavily off balance to the west and will remain so

until the telescope is finally assembled. The brakes of the right ascension assembly motions will hold the assembly in position, but if they are released without someone holding the instrument, the whole assembly will fall to the west and damage will result. After the right ascension assembly is securely attached to the stand, the latitude turnbuckle should be connected. The motions of the right ascension assembly should then be loosened and the assembly turned so that the mounting brackets for the main frame are on the east side and horizontal. Then secure the brakes.

The main frame with the guide telescope attached is stored in one large box. Two men can easily pick it up and bring it to the waiting pedestal. It is very large and bulky, but only weighs about 100 lbs. A third man is required, however, to secure the frame to the right ascension assembly. This is again done with four bolts. The telescope as thus assembled is nearly in balance but again the brakes of the right ascension assembly must not be released without someone ready to guide the telescope.

The secondary mirror is already mounted in a portion of the frame which is stored in the mirror box. This should next be attached to the main frame using six bolts. The primary mirror is secured in the mirror housing which is also stored in the mirror box. This housing is next attached to the main frame by six bolts.

There is real danger of serious damage being done to the mirror if, as it is being brought into position, it slips from your grasp. The safest method is to have the frame inclined upward and bring the mirror housing up from below for positioning.

The clock drive mechanism is next attached to the south side of the stand, but the reach rod to drive the right ascension assembly should not yet be secured.

The tubular light shield should then be inserted inside the frame and screwed into the hole in the center of the primary mirror.

The last step in assembly prior to balancing would be to insert the main and guide telescopes' eyepiece and photocell unit in their respective receptacles. This is a snap-twist retaining system and requires no bolting.

The assembled telescope can now be tested for balance. There are boxes of lead weights which can be attached to counter-weight bars on the main frame and on the right ascension assembly. Point the telescope at the meridian, say towards the celestial equator, release the right ascension brake and observe the direction of motion of the telescope. If it is not balanced, it will fall east or west. Add weights as necessary to the main frame or right ascension assembly to counter-balance the motion. Continue this procedure until the telescope does not fall and a gentle push

in each direction has no appreciable difference in the ease of motion. Secure all the weights and the right ascension brake. Next, loosen the declination brake and test for balance on this axis. The counter weight bar on the main frame extends on both sides of the declination axis, and by moving the weights along the bar, balance can be obtained similar to the procedure above. Now we can connect the reach rod from the clock drive mechanism to the right ascension assembly.

The clock drive weight tripod should be erected about 15 feet south of the telescope and the wire from the clock drive mechanism strung through the pulleys and attached to the weights.

Finally, the latitude of the site should be set into the right ascension assembly to point the rotational axis approximately parallel to the earth's rotational axis. This is done by turning the latitude turnbuckle until the dial reads to the nearest degree. There are four of these latitude turnbuckles and the proper one for the area should be selected. The ranges of adjustment are 0°-21°, 0°-31°, 20°-50°, and 45°-50°.

A photograph of the completely erected telescope is included as Figure (3).

Figure 3. - Photograph of the Nippon Kogaku Co. Occultation Telescope assembled.

3.3 Adjustment

The various adjustments which must be made on the telescope before it can be used for observations group themselves naturally into two categories. One category contains those adjustments made on the optical elements of the telescope, and is called collimation; The second category contains those adjustments made on the mechanical movements of the telescope, and is called alignment.

3.31 Collimation of the Telescope

A telescope is said to be collimated when the optical elements have been adjusted to direct light to the receiving element with minimum distortion and aberration. Collimation, therefore, is the process of "lining up" the mirrors and lenses until, when the telescope is pointed at a star, the star image at the eyepiece is as bright and symmetrical as it is possible to get it. This insures that the telescope optical system is working at maximum efficiency.

The telescopes designed for occultation observations utilize Cassegrainian optics consisting of a 30 cm paraboloid primary and a 8 cm hyperboloid-convex secondary. The optical system comprises, in the order in which the elements reflect or transmit incoming light, the primary, the secondary, a 90° prism, and an

eyepiece; the approximate relationships are shown in Figure 4.

A simple method of collimating this system is described below. It gives good results in a short period of time. There are numerous variants of it which the observer may prefer, once he starts work and becomes familiar with the mirror relationships and their adjustments. The procedure falls into two parts, the major work being done in the daytime and the final adjustments done at night on a star.

We must assume that the components have not been greatly disturbed in their mountings during shipment, and retain the basic relationships of collimation after the telescope is reassembled. Thus, we assume that the secondary mirror is mounted in the center of the frame so that the optical axis of the telescope is defined to be the line through the center of the secondary mirror and the center of the hole in the primary. The observer should remove the eyepiece and photocell unit from the back of the primary mirror housing and look up through the hole. If he centers his eye so that he sees the hole in the primary concentric with the far end of the frame, his eye will be on the optical axis. Looking into the secondary, the observer will see an image of his own eye in the secondary at some point which will not be in the center of the mirror, in general. The normal to the mirror where the image is formed

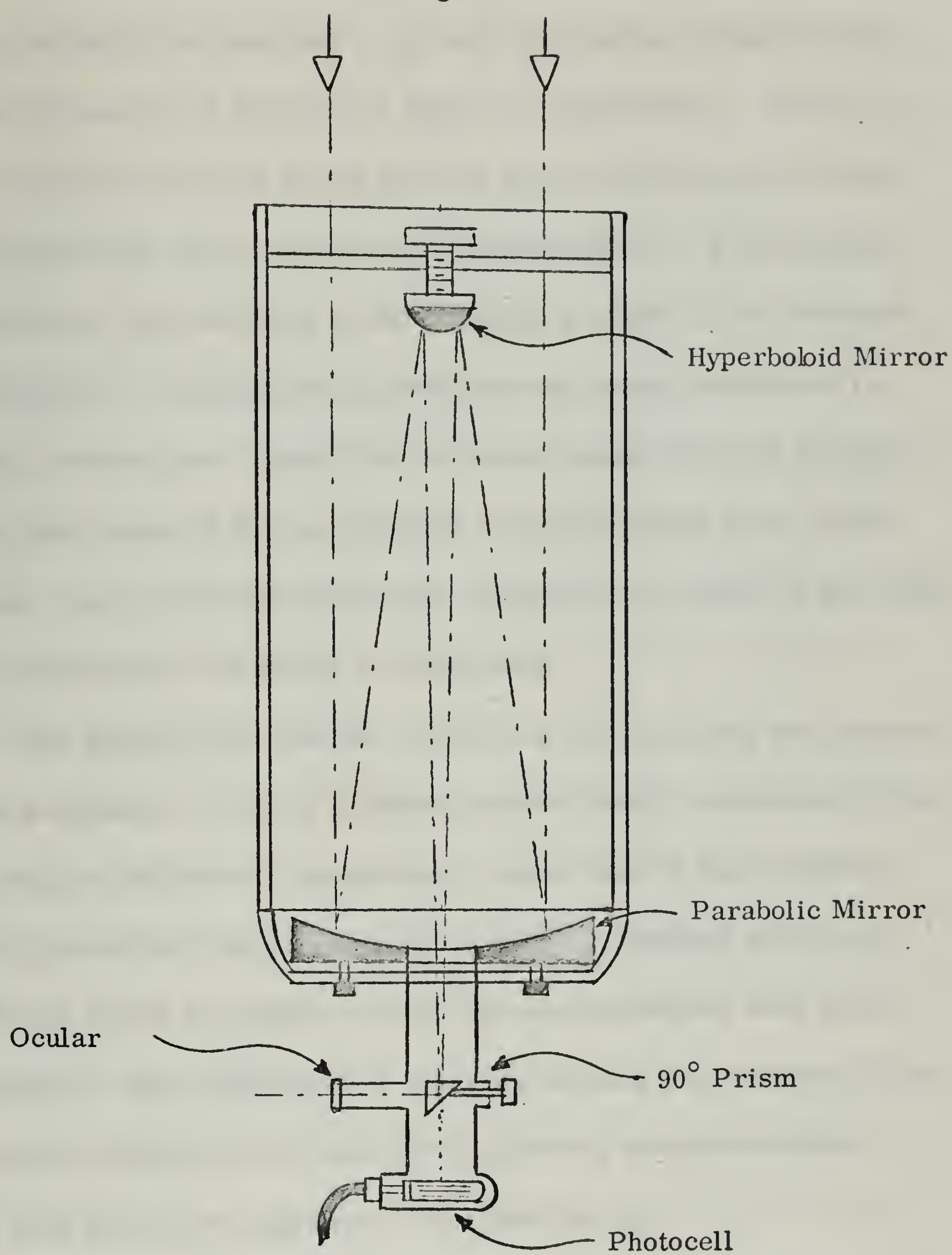

Figure 4. - Cassagrainian Telescope Optical Path

passes through the observer's eye and this normal should be normal to the center of the mirror when it is collimated. Hence, we must adjust the screws on the back of the secondary mirror until the image of the eye is centered in the secondary. If this cannot be achieved, then the axis of the secondary mount is not centered in the frame. It should be adjusted and the whole procedure repeated. Moving one side of the secondary away from the primary causes the image of the eye to move away from that side. When the eye, centered on the optic axis, sees its own image at the center of the secondary, the latter is collimated.

The primary can now be collimated by rendering the images of the secondary, as seen in the secondary itself, concentric with the image of the hole in the primary, also seen in the secondary. Moving one side of the primary toward the secondary will move the image in the secondary toward the corresponding side of the secondary. The adjustment is made by turning one or more of the 3 capstain screws on the back of the primary mirror housing. They pull the mirror against a tensioned spring.

The ocular and 90° prism are sealed in a metal casing and cannot be adjusted in the field. If this unit is damaged in transit, it must be returned to an optical laboratory for repair.

The telescope is now collimated accurately enough to proceed

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to the alignment procedures in the next section. After alignment, the following checks should be made on a star at night. The eyepiece is inserted into the back of the primary housing and the telescope pointed at a bright star. The clock drive should be engaged and the telescope permitted to track the star during the following adjustments. The focus screw on the eyepiece should be turned to bring the star into a sharp image. If this cannot be done the secondary mirror should be moved toward or away from the primary, altering the focal length to achieve sharp focus. This will probably introduce slight collimation errors but the following steps will eliminate all residual errors.

In a telescope that is properly collimated and focused, the observer will see a star as a bright point of light with a small halo effect around it in a concentric circle. If the halo or ring is not a circle but an ellipse, the telescope is out of collimation. The observer should slightly move the ocular out of focus, thus enhancing the ring effect, and adjust the capstain screws on the back of the primary housing to make the halo circular. This must be done very carefully as a slight movement of the screw will cause the star to change its apparent position in right ascension and declination. The fine movement for these motions must be turned simultaneously with the capstain screws in order to keep the star in the

field of view. If these screws will not completely remove the circular distortion of the "halo", the secondary is too far out of collimation and the procedures described above must be followed to collimate the secondary. At night, satisfactory results can be obtained by shining a flashlight at the observer's eye from within the frame. This will provide enough illumination to use the eye method. After the "halo" has been made circular, the eyepiece should be focused again and a check made on the star image.

3.32 Alignment of the Telescope

For the telescope to track a star, it is necessary that it rotate: (1) at the same rate as the earth; (2) about an axis parallel to the earth. The rate of drive is easily adjusted by regulating the rate of the clock drive mechanism, which is done by turning a knob for faster or slower. Outlined here is a method of aligning the axis of the telescope with the earth's axis.

Assume a small arbitrary error in the polar alignment, which we know must be the case on initially setting up the instrument. This error can be resolved into two parts: an altitude error and an azimuth error. If we track a star on the local meridian we will see that the altitude error has no effect on the tracking. Whether the pole is high or low the telescope will drive due west. Hence,

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the only effect we detect on the meridian is the azimuth error. Observations made on the meridian, then, tell us what the azimuth error is and how to eliminate it. When this has been done, all that remains is the altitude error. By a line of similar reasoning, one can see that the azimuth error causes no drift in the prime vertical, while the altitude error gives the maximum effect. To a very good approximation, errors in polar alignment do not cause a drift in right ascension. Any drift noted in right ascension, therefore, is due to the speed of the drive motor, and this should be ignored in this procedure.

Summarizing, in tracking a star on the meridian, the star will drift south if the pole is east and drift north if the pole is west. In tracking a star in the east or west, we see; (1) if the pole is high, the star drifts north in east, south in west; (2) if the pole is low, the star drifts south in east, and north in west.

An approximate alignment of the telescope axis can be secured as follows. First, align the guide telescope to the main telescope by pointing at some remote object. Set the telescope so that the declination circle reads exactly 90°, and swing the telescope around the polar axis until it is nearly east of the stand. Note the configuration of the stars as seen in the guide telescope. Now turn the telescope around the polar axis so that it goes west of the

stand. If the axis is correct, the field should remain the same. If the field moved up or down, this means that the latitude was not set in correctly. The telescope should be moved in altitude by adjusting the latitude setting until the field reaches a position midway between the two previously observed positions. The field should not now move when the telescope is put back on the east side.

Now set the telescope to the declination and hour angle of Polaris. The setting should be to $0^{\circ}.1$ in declination, and to the nearest 5 minutes in hour angle. Adjust the altitude and azimuth of the polar axis by turning the latitude turnbuckle and the pedestal on its base until Polaris is brought to the center of the field. This method of setting takes only a few minutes.

Precise alignment is accomplished by observing a star on the meridian centered in the aperture of the eyepiece. After some short time of tracking, observe the direction of the drift in the aperture and adjust the push-pull screw on the south foot of the pedestal to compensate for error in azimuth. The same procedure is followed on an east or west star, this time adjusting the latitude turnbuckle for altitude errors. When the star does not drift out of the hole after fifteen minutes, the error in that coordinate may be considered to be eliminated.

3. 33 Adjustment of the Guide Telescope

The main telescope, with its 30cm mirror, has a field of view of about 8 minutes of arc, and, therefore, covers an area of some 50 square minutes in the sky. This is a very small area compared with that covered in a glance by the naked eye, and even compared with that seen through a good pair of binoculars. Locating a star directly by its relation to known stars or constellations is obviously impossible using the main telescope alone. A second shortcoming of the main telescope is that, while it is perfectly satisfactory for the observation of disappearances, since the occulting star can be kept under observation up to the moment of disappearance, the telescope is not accurate enough to track a star during its hour or so behind the moon and then pick it up again upon its reappearance, or emersion.

The guide telescope supplies the means of overcoming these two handicaps. It is a 10cm refracting telescope with an instantaneous field of view of some 120 minutes of arc, or an area coverage of 11,000 square minutes. It is therefore extremely useful for the location of stars.

The optical elements, other than the eyepiece mounted on a removable micrometer head, are fixed inside the tube, and as this is not disassembled for transportation, it can be assumed that

the collimation remains fixed. The guide telescope tube is secured to the main frame, and the alignment of the axial center of the tube to the main frame is not disturbed in transportation. The adjustable micrometer head for the eyepiece permits adjusting the optical axis of the guide telescope at any given setting of the main telescope within a field of 9° of arc.

In the observation of occultations, the star which is to be occulted is first located in the guide telescope with the micrometer head set so that the optical axis of the guide and main telexcopes are parallel. The star is then located in the main telescope and centered in the aperture. The micrometer head of the guide telescope is then adjusted until another star which will not be occulted is found in the field of view, the main telescope being left pointed at the occulted star. This auxiliary star, or guide star, is then kept at the intersection of the cross-hairs in the reticle. As long as the guide star is kept centered therein, the main telescope will be pointed accurately at the occulting star.

It is extremely important that the occulting star be located as early as possible. This should be done several days before the occultation, if possible, and the guide telescope placed on the guide star at that time. This will permit the observer to pick up the occulting star immediately on the night of the occultation. Otherwise,

as the occulting star will usually be less bright than a selected guide star, there may be difficulty in finding the star if lighting conditions are poor.

3.4 Assembly of the System

The accompanying block diagram, Figure (5), shows how the various pieces of equipment are connected together. The gasoline engine generator, which supplies the electrical power for operation of all the other equipment, must be placed as far as possible from the telescope. It should not be allowed to rest directly on the ground if some means is available for supporting it properly. A spare tire is a very good support, cushioning the engine's vibrations effectively.

3.41 Photomultipliers

The photomultiplier tube, like the human eye, "sees" light. Without going into detail about the theory and construction of photocells, we can say that a photomultiplier is a device which converts light falling upon it into a tiny electric current which is proportional to the light intensity (of the order of a millionth of an ampere for the starlight we use). This current, amplified by the Brush amplifiers, is what causes the pen of the oscillograph to deflect. The photocell-amplifier combination must be able to "see" the

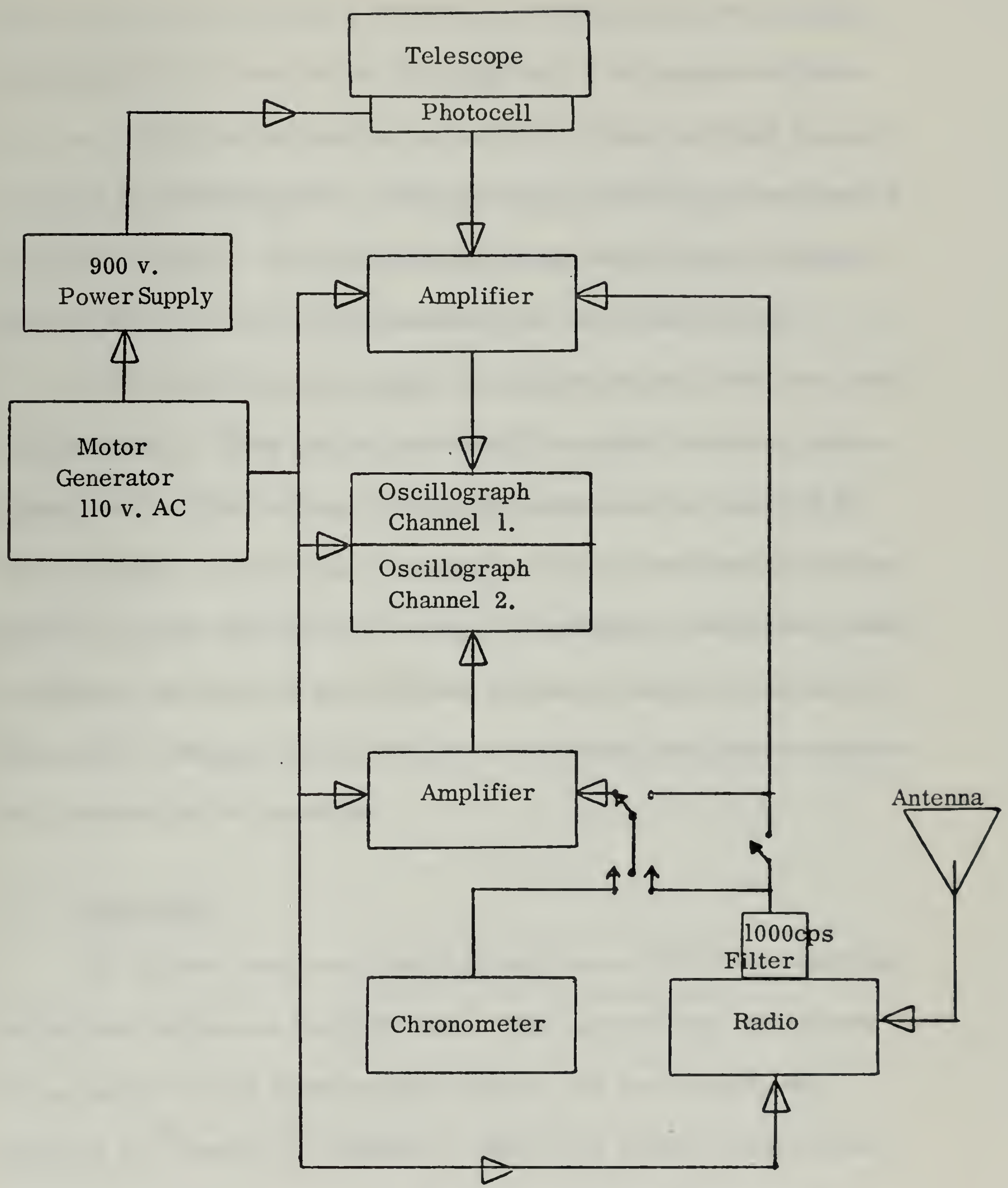

Figure 5. - Block Diagram of Equipment Hookup

faint stars we use. Hence, it must be protected from the intense moonlight; this is done by an iris aperture in the eyepiece/photocell unit, which can adjust the aperture to let the starlight through and keep the moonlight out. The photocell should never be exposed to bright daylight. This will shock the tube with intense light and will increase the noise characteristics of its output current.

A 900 volt DC power supply is required by the 1P21 tube used in this system. This can be provided by a simple rectifier power-supply circuit with voltage divider that produces the required 90 volt DC steps. An alternate method is to use a combination series/parallel circuit with ten 90V. radio "B" batteries, which are readily available, and several sets of these batteries should be included in the site kit. Sample curcuit diagrams for these two power supplies are included in the appendix.

3.42 Amplifiers

The current output of the photocell varies with the brightness of the light falling on the photocell. This current can, therefore, be expected to vary between wide ranges, all very small, say between 10^{-5} and 10^{-11} amperes. This very small current to be measured, therefore, requires use of an amplifier between the photocell and the oscillograph. The amplifiers used in this system

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are 5 stage DC amplifiers which can multiply the input voltage by a factor of 10^{+3}.

A complete description of the Brush Electronics Company amplifiers, model BL-932, is given in the instructions manual provided with each amplifier, and will not be given here. Every operator should familiarize himself with the contents of the manual, and should pay particular attention to the instructions for "balancing" the amplifier. These amplifiers depend for their stability upon the very careful matching of the 6F5 tubes in the first two amplification stages. These tubes lose some of their "match" through jolts in transit, through heating, and with time. The similarity lost through movement is usually slight and can be compensated for by adjustments on the amplifier. Heat-induced variations are often quite large, and not able to be compensated for within the amplifier. Extra "matched pairs" of the 6F5 tube are carried as spare parts in the event that replacement is necessary to achieve balance. The amplifier should be given as much ventilation as possible, and if some ice can be procured and placed so that air moves across it to the amplifier, the electronics will perform much better.

3.43 <u>The Oscillograph</u>

The signals transmitted by the photocell through the amplifier are recorded on an oscillograph. This instrument is simply a D'Arsonnal galvanometer which has an ink pen attached to the moving coil. The coil, moving in response to the signals from the amplifier, moves the pen to and fro across the strip of chart paper which is itself moved under the pen at a constant rate. The instrument used in this system is the Brush BL-202 oscillograph, which has two galvanometers, and is able to record signals from two different sources simultaneously. One channel is used to record the photocell output and the other for the time marks.

3.44 <u>Radio</u>

The radio is an extremely important item of equipment since it is this instrument which provides the time signal by which the instant of occultation is determined. Therefore, one of the criteria which <u>must</u> be considered in choosing a final station location is the quality of reception there.

Before a decision is made, the radio should be set up at the point in question and the reception of WWV, or other time source, estimated. An antenna should be erected to improve reception. A simple check on the volume will be sufficient; an inaudible signal will be unsatisfactory unless no other site is available. In the

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latter case, a more complete test involving connection of the radio to amplifier and oscillograph should be made. Be sure to check all the bands for a time signal, as the various bands will have different strength of signals for varying times of day and night. The time signal should not be led directly to the amplifier, unless no other alternative is at hand, but should be sent first through a 1000 cycle band pass filter. This filter removes most of the 440-cycle and 600-cycle tone which forms the background for the 1000 cycle pips, which are WWV's time signals.

3.45 The Chronometer

The chronometer is an auxiliary time-source for use when the radio time signals fail. It should be set up and running for every occultation, regardless of the quality of the reception, since the possibility of radio failure at the crucial moment is always present.

In setting up the chronometer, remove the box carefully from the container, holding it by the leather strap. Undo the strap and open the cover. Undo the electrical binding knobs and remove the chronometer from the box. Unscrew the glass cover, set aside, and invert the chronometer case, letting the clock mechanism fall out gently into the hands. Place the case aside and carefully remove the cork wedges under the balance wheel. Replace the

chronometer in the case, screw on the cover and replace the chronometer in the gimbals. Wind the clock and refasten the electrical knobs.

As long before occultation time as possible, the relationships between radio signal time and chronometer time should be established. Connect the radio into channel 1 amplifier and the chronometer into channel 2 amplifier. The radio and chronometer signals are now being recorded on the two separate oscillograph channels. Run the oscillograph at slow speed long enough to get the times of the ticks written down on the chart; then change to 125mm/sec speed for about 20 seconds. This will permit comparison to 0.01 second. Change back to slow speed, record times again, and stop the oscillograph. Repeat this testing every half-hour or so, and as close to occultation time as practicable. Save these tapes for later comparison. When it is close to occultation time and no longer feasible to use both amplifiers for testing, switch the radio to channel 2 and record both time signals on the same channel. A final 125mm/sec comparison of both singals on the same channel should be run about 5 minutes before the occultation.

For recording the occultation, use judgment based on the quality of the radio signal, as to whether the radio signal or the

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chronometer signal should be recorded. Either will give acceptable results if the comparison above has been done correctly. It may be advisable to record both time sources during the occultation, insuring that the pips are not coincidental and that they are properly identified. The observer must be careful when using WWV that the minute of Binary coded time transmissions does not cause the oscillograph pens to become erratic. As soon as possible after the occultation, reconnect the radio to channel 1 and record both time signals again.

3.5 <u>Observation of the Occultation</u>

3.51 <u>Location of the Star</u>

As soon as possible after collimation and alignment of the telescope, the star to be occulted should be found and its position memorized. One method to find the star is to set the star's right ascension and declination on the telescope's circles. This will point the telescope at the star's approximate position (because of errors in the circles and in alignment), and the star itself may be found by searching the field.

The most accurate method is to locate two stars which are known to be in the neighborhood of the occulting star, and to measure the distance between them in terms of the telescope's R. A. and declination circles. The program star is then located by

moving from one of the reference stars the amount and direction indicated by the relation between the telescope measurement and the known value of the distance between the reference stars.

3.52 Tracking

As soon as the program star has been found, whether it will disappear or reappear, the guide telescope should be fixed on a reference or guide star which will not be occulted. Tracking of the program star should then be carried out largely through the guide telescope, but with frequent reference to the main telescope. The arrangement of the eyepiece/photocell assembly precludes visually watching the occultation through the main telescope due to the push/pull 90° prism. The light from the star may be directed through the eyepiece or to the photocell. The iris aperture should be adjusted to the smallest opening practicable to restrict all but the starlight from reaching the photocell. While checking for tracking in the eyepiece, watch to see that the star remains inside the aperture.

3.53 Occultation Procedure

All equipment should be in working order and running in normal condition at least one hour before the scheduled time of the occultation. Particular caution should be used when starting the

amplifiers and oscillograph. The following sequence of steps is recommended and should be developed into a habit.

(a) Before turning the instrument on, make sure that the gain control and calibration voltage are as far counter-clockwise as they will go. The gain will be set around zero, and the attenuator at 100. The balance knob should be at the half-way point (this knob has ten complete rotations).

(b) Turn the amplifier on.

(c) Insert the signal plugs into the amplifiers.

(d) Let the amplifiers warm up for at least five minutes, preferably for ten minutes.

(e) Start the oscillograph.

(f) Move the pens to their central position using the balance knobs (check the mechanical balance on the oscillograph to make sure that they are not biased).

(g) Adjust the gain for proper amplitude of deflections of the pens.

(h) If improper amplitude, move gain to zero and adjust the attenuation.

(i) Readjust the gain as necessary for proper amplitude of the pens.

(j) With the system tracking the program star, adjust balance knob to move the pen a little off center.

(k) With a piece of cardboard or plywood, manually "occult" the program star by passing it in front of the main telescope. Observe the deflections of the pen and adjust the attenuation and gain until the best trace is recorded on the oscillograph.

At this time a final check should be made that the proper star is being tracked. The moon moves eastward with respect to the stars by a distance equal to its own diameter every hour. The program star should be about one moon diameter to the east of the moon, and should obviously lie in its path.

About ten minutes before the scheduled time of the occultation, the oscillograph should be put on slow speed, and an assistant begin calling out the minutes and marking them on the tape. The clock drive weights should be cranked up to the maximum height to insure that the clock will run through the occultation.

Five minutes before the occultation, a final chronometer and radio check should be recorded on fast speed for about 20 seconds. The quality of the radio time tick should be evaluated and a decision made as to whether or not the radio signal will be recorded.

One minute before the scheduled time, the assistant should turn the oscillograph chart speed to medium and start calling off the seconds. He should carefully watch the radio time signal for fading. The observer tracking the star in the guide telescope should insure the star is centered in the cross hairs, and be prepared to actuate a hand stop watch at the instant he observes the occultation.

Forty seconds before occultation time, the chronograph drive should be turned to fast speed. The assistant will continue to call the seconds until the occultation is known to have been successful or unsuccessful. The paper drive should be left on fast speed until then.

A mark should be made lightly on the paper at the moment the occultation is believed to occur, as marked either by a noticable deflection of the pen or by the observer's calling that the star has disappeared. If the only evidence of the occultation is the observer no longer seeing the star, the oscillograph should be left running for at least a minute and the time called out as before, since it will often happen that the observer sees the star disappear either before or after the actual time of disappearance.

When the occultation is definitely over, the oscillograph is stopped, the assistant stops calling the time, and the time at

which the oscillograph was stopped is marked on the tape at the point of stoppage. The observer should also stop his watch at this time, and then it is very easy to subtract the number of seconds indicated on the stop watch from the time ticks on the tape. This should correspond to the second at which the occultation should have occured and serves to check the assistant's time marks.

Before ceasing operations, the following work must be done, whether the occultation was successful or not:

(1) The tape is picked up carefully.

(2) All the tape, from and including the point of stoppage up to the point one minute before the time of occultation, is retained; if important information occurs before this point, this portion of the tape is also retained.

(3) The predicted, and, if successful, the actual occultation points are clearly indicated. The seconds for the entire minute within which the occultation did, or was predicted to occur, are written on the cooresponding time-ticks.

(4) The date, approximate time of occultation, location of the station, and the star occulted are written on a permanent portion of the tape.

(5) Notes should be made on the tape itself of:

(a) Whether time ticks are radio or chronometer.

(b) Radio station and frequency used.

(c) Chronometer used.

(d) Weather conditions.

(e) Amplifier settings.

After a successful occultation, a time comparision tape should be made as soon as possible, showing the radio time signal and chronometer signal on an adjoining channel. A tape covering about 30 seconds is sufficient. A reproduction of an actual occultation tape is encluded as Figure (6) and the deflections of the oscillograph pens are clearly seen.

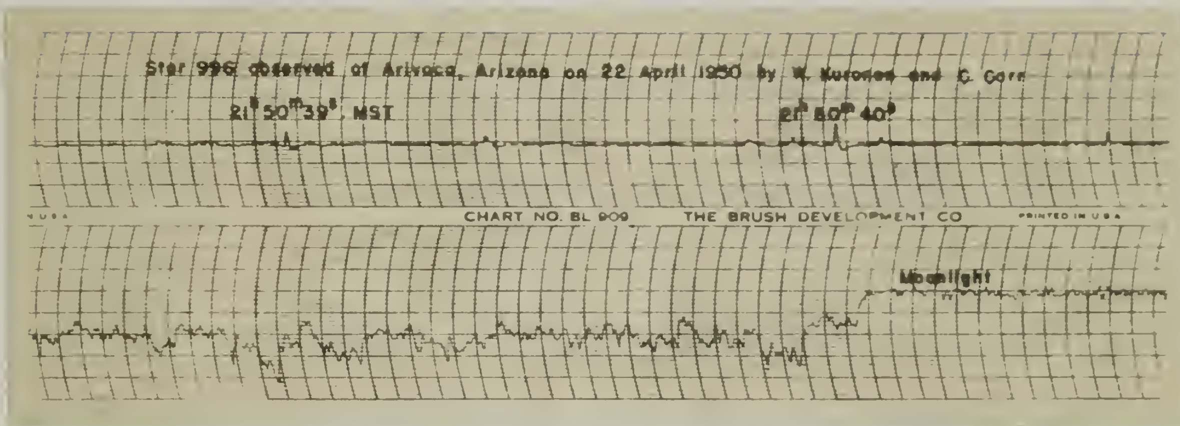

Figure 6. - Oscillograph Tape of an Occultation [Army Map Service].

CHAPTER 4

REDUCTION OF DATA

The first step in reduction is the measuring of the oscillograph tapes to determine the time of the occultation at the site. This time must then be corrected for several factors. The first of these is the propogation delay of the radio signal from the site of the transmitting station to the observer. Next we must add the correction for the broadcast time errors at the transmitting site. The correction for the variation of latitude caused by the motion of the pole must be included to obtain UT1 and then UT2 can be obtained by applying the correction for the seasonal variation in the rotation of the earth. When all these corrections are taken into account, the total time uncertainty has been found to be less than 0.01 seconds [Henriksen, 1962].

We must then proceed in the reduction according to which method we have selected. The Equal-Limb-Line method will be discussed first. We can see that what we are trying to do is to correct the position of the unknown site. This can be accomplished by successfully observing at least two occultations from the unknown

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site to any two places in a known geodetic system. Each successfully observed pair of occultations results in obtaining one line of position at the unknown site. In the prediction computations, a mean radius of the moon has been used. Since the observed value of the lunar radius is the crux of the reduction theory, it may be well to say a few words about it now.

Because of the mountainous character of the moon, and the irregular edge that it presents as a result, the radius of the visible moon varies all around its perimeter. Each favorably observed occultation provides an equation for each site of the form:

$$\sigma^2 = (\xi - X)^2 + (\eta - Y)^2$$

At the known site we may assume that ξ and η are known. Also, we know that X and Y, the moon's coordinates on the fundamental plane, may be slightly in error, but the error will be the same, for all practical purposes, at each end of the equal-limb-line.

If the geodetic coordinates at the unknown site were correct, the σ obtained there would be equal to that obtained at the known site on the equal-limb-line. However, this seldom occurs, and we blame the descrepancy on the incorrectness of the position adopted for the unknown site. As a result, the observations at the known site are used, in effect, to correct the astronomical data, to get an observed radius of the moon at the point on the limb where

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the occultation occurs. It is understood that the observed radius is, in part, a fiction; it absorbs not only genuine corrections to the moon's radius, but also the radial component (at the given position angle) of the error in the moon's position. Since each pair of observations are made at the same point on the moon's limb, and since only the radial component affects the time of occultation, this device is justified.

With the lunar limb corrections possible since Dr. Watts' charts have been published, the residual errors in the above assumption are negligible. These charts have been mentioned several times previously and a brief description of their use is now included.

In determining the lunar limb correction, we are interested not only in the topography at a given point, but the total radius of the moon at this point. This total radius will change at a given position angle as the librations of the moon cause the visable edge to change. The librations will present a different aspect of the same topographic feature and, in effect, change the effective height of the feature above the mean radius of the moon. This effect is illustrated in Figure (7). The arguments for entering the table are:

Ω = Position angle from the central meridian of the moon

l = Libration in longitude

b = libration in latitude

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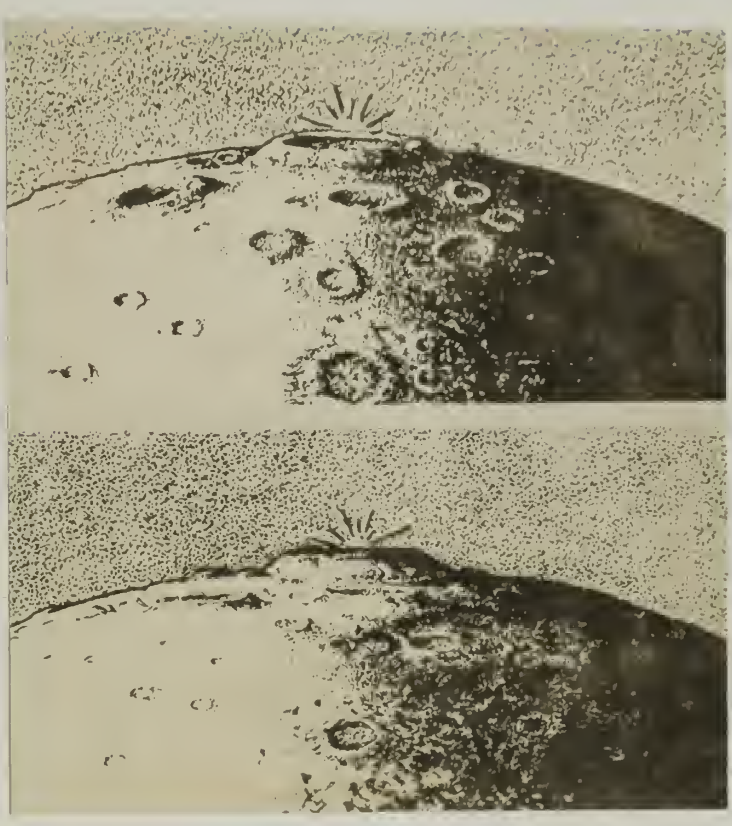
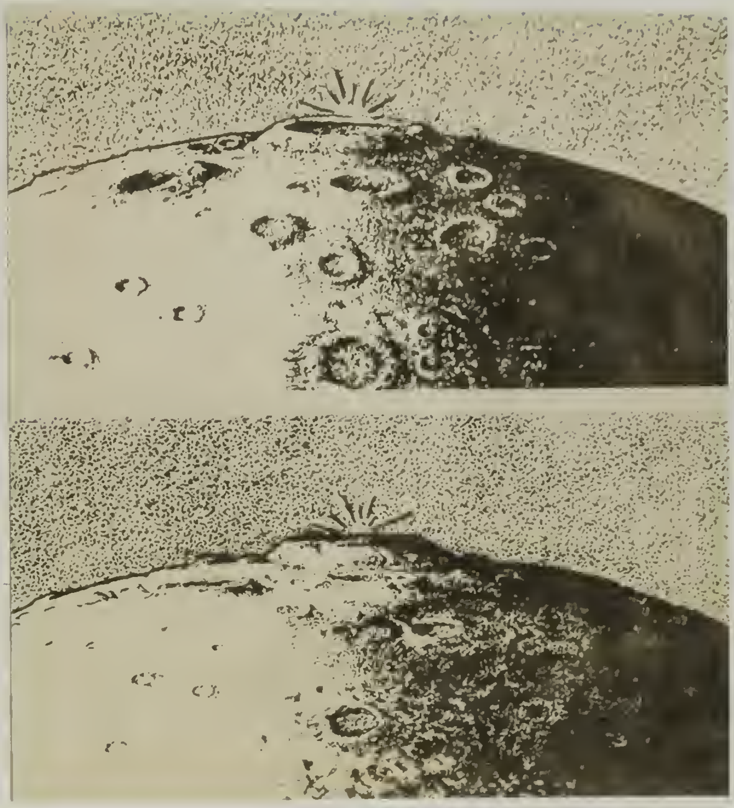


Figure 7. - Artist's sketch of the changing face of the moon's limb due to the librations of the moon. The star is being occulted by the same topographic feature, but the observed radius will have changed during the time lapse between the two observations. [Army Map Service sketch]



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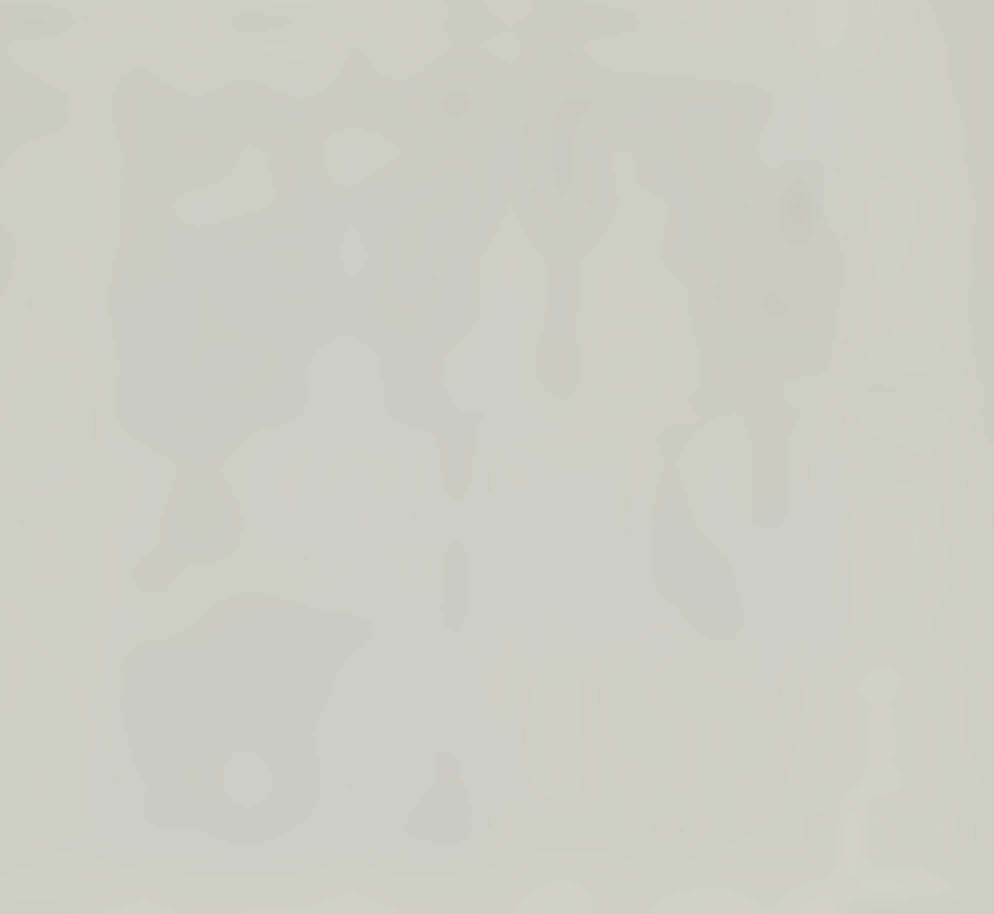

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These values can be obtained from the prediction computation and interpolation in the Ephemeris to the time of observation. With these arguments, the charts give the amount of the irregularity on the moon's limb in the direction of the star when the moon is at its mean distance from the earth. The quantity must accordingly be corrected by the ratio of the actual to mean semi-diameter based on the parallax at the time of observation. Though not included in chapter 2, this procedure must be done in the initial prediction of an equal-limb site. Due to librations, the observed radius of the moon, even at the same position angle, can be considerably different at stations a thousand or so miles apart. The time lapse between the observations does permit the libration effect to become significant.

There are several other corrections that also must be considered in the final determination of the time of contact. One of these comes from refraction of the ray of light from the star in the earth's atmosphere. In Figure (8), the line MA represents the true path of light from the moon to the observer, and MB the straight line path of light. It is evident that an observer at A sees an apparent contact at the instant an observer at B would see a true contact if there were no refraction. Thus, the distance AB should be added to the geocentric radius in computation for the

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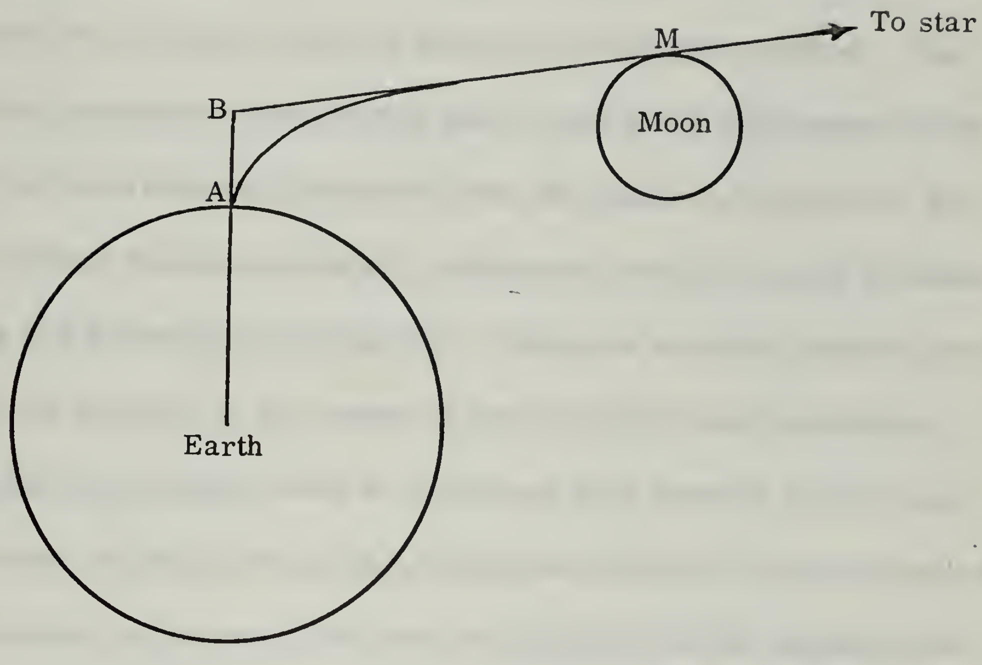

Figure 8. - Refraction of the atmosphere effect on changing the geocentric radius used in computing the Besselian coordinates..

Besselian coordinates of the point. Tables have been published [Chauvenet, 1863] which give the correction as a function of the Z coordinate of the observer. In these tables it can be seen that if the altitude of the moon at contact is greater than 20°, the correction is negligible.

Other corrections that must be considered arise from the datum of the "control point" in the equal-limb-line method. The height of the observer above the geoid, and the displacement of the center of the reference ellipsoid from the center of gravity of the earth, affect the true geocetric radius that should be used in determining the Besselian coordinates. The moon's orbital path is computed with respect to the center of gravity of the earth and both Besselian coordinates must be computed with respect to the same reference. If the center of the reference ellipsoid is not corrected to the center of gravity, the fit of the ellipsoid at the unknown site will be increasingly inaccurate as the distance from the datum of the reference ellipsoid increases. In simple terms, this means that the coordinates computed for the unknown site will have large undulations of the geoid. It becomes imperative that proper Besselian coordinates be used if the control points of the various lines of position obtained from different occultations are located on separate datums. Further discussion of these datum errors

and methods of computing the corrections can be found in [Henriksen, 1962].

The final solution of the position determining problem can be obtained by subtracting the σ of the unknown station from the σ of the known, the remainder being the error $\Delta\sigma$ caused solely by the error in latitude and longitude. The astronomical errors have the same value at each end of the equal-limb-line and do not enter the problem. Care must be taken to include all the corrections, as this is a straight numerical solution. The value of $\Delta\sigma$ is then used to determine the intercepts on a local coordinate system, to obtain the line of position. This method, and the local coordinate system used, is explained in [Henriksen, 1957] and [O'Keefe and Anderson, 1952].

An approach not involving straight numerical reduction would be the solution of a series of observation equations, each of the form:

$$\Delta T = a\Delta\lambda + b\Delta\varphi + c\Delta\alpha_M + d\Delta\delta_M + e\Delta\Pi_M + f\Delta K_M + gN$$

One such equation can be written for each observed time of contact, where ΔT is the difference between the observed and the computed contact times. In these equations the quantities $\Delta\lambda$, $\Delta\varphi$ and N represent corrections to the assumed geodetic coordinates. The quantities $\Delta\alpha_M$ and $\Delta\delta_M$ are corrections to the moon's tabulated

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α and δ ; and $\Delta\Pi_M$ and ΔK_M are corrections to the parallax and semi-diameter of the moon.

For occultations observed on each end of the equal-limb-line, the astronomical terms are assumed to be constant, the number of unknowns reduces to the geodetic unknowns, and a least squares solution is possible with only a few observations. If many observations are available, then the assumption that the astronomic unknowns are constant can be ignored, and the least squares method used to find values for the geodetic unknowns to a very high degree of accuracy.

Reduction of data in the Single-Site method also uses this least squares method for determining the position of the site. At the station, the unknowns $\Delta\lambda$, $\Delta\varphi$, $\Delta\Pi_M$, ΔK_M and N, of the above observation equation, will remain the same for all occultations observed. Each occultation, though, will introduce two additional unknowns, $\Delta\alpha_M$ and $\Delta\delta_M$, the corrections to the tabulated position of the moon. During a short period of time these last corrections should not vary appreciably, so, for all occultations observed in any one night, $\Delta\alpha_M$ and $\Delta\delta_M$ can be treated as constants.

If n is the number of nights occultations are observed, the total number of unknowns will be 5+2n. By observing more than

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two contacts per night, the number of observation equations will easily overtake the number of unknowns and a solution will be possible. It is not uncommon for more than seven occultations of stars of ninth magnitude and brighter to occur during one night [St. Clair, 1961].

This method would have been the only way to reduce the single-site method prior to the Watts charts and the improved lunar emphemerides. More than two contacts per night would have been required for a solution. However, using the approach that right ascension, declination and parallax of the moon can be computed numerically correct for a given time, and that the unknown K_M, error in the semi-diameter of the moon, can be completely eliminated with the Watts charts, there remains only the three geodetic unknowns in each observation equation. Thus, with as few as 6 to 8 observations at any station, any of which could be taken on the same or different nights than the others, a least squares solution would give very good corrections to the station's assumed coordinates. Actually, only 3 observations would be required to give provisional values, but because of residuals in the assumptions, the more observations available the better the results would be.

The coefficients of the observation equations above can be

found in [Mueller, 1964] and [St. Clair, 1961], and the method of least squares solution of occultation observations is demonstrated.

CHAPTER 5

INSTRUMENTAL INVESTIGATIONS AND CONCLUSIONS

5.1 The Telescope

In the Spring of 1967, the Department of Geodetic Science, of the Ohio State University, received, on loan, from the Army Map Service, an occultation telescope kit. This telescope was one of six manufactured in Japan, by the Nippon Kogaku Co., for the Pacific Occultation Program. It is of the Cassegrainian Reflecting type with an overall focal length of 5 meters and a primary mirror diameter of 30 cm.

When the equipment was received it was assembled by some members of the staff of the Geodetic Science Department, but the system would not work. This observer became interested in the equipment in October, 1967, and started a systematic effort to put things into operating condition.

The immediate problem encountered was that the telescope was not properly adjusted. Preliminary collimation and alignment were done using the procedures outlined in chapter 3. It was found, after repeated attempts to achieve collimation, that the final image

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When the equipment was received it was assembled by some members of the staff of the Geodetic Science Department, but the system would not work. This observer became interested in the equipment in October, 1967, and started a systematic effort to put things into operating condition.

The immediate problem encountered was that the telescope was not properly adjusted. Preliminary collimation and alignment were done using the procedures outlined in chapter 3. It was found, after repeated attempts to achieve collimation, that the final image

of a star could not be brought to a single point. Instead, there was a principal image, and very close to it, a secondary image of much less intensity. The primary mirror was then removed from the telescope and taken to the optical laboratory at the Physics Department. There the mirror was set up in an optical bench, and a series of tests conducted to check the mirror's curvature. The knife edge test [Texereau, 1957] was used and no significant irregularities were found. However, when the mirror was used in the optical bench and the light rays from an "infinite" source focused, there was observed the two focal points. After consulting with representatives of the Physics, Optometry, and Astronomy Departments, the consensus was that the mirror was not a true paraboloid. It was considered that the effect of the silvering being worn considerably in a sector of about one fourth of the mirror, had caused the rest of the mirror to focus at the principal image, while the worn sector was focusing at the secondary image. It was concluded that the problem could have been corrected by resilvering the mirror. As the time and funds were not available to accomplish this, another method of correction was attempted.

Prior to remounting the mirror in the assembly that contains it on the telescope, a small wooden block was glued to the back of the mirror, centered in the sector that had the worn silvering.

[illegible]

The theory behind this was that during collimation the mirror could be warped very slightly in this area as the adjusting screws were tightened. Thus causing the "bad" sector to focus on the same point as the rest of the mirror. Naturally, great care had to be used not to crack the mirror during the process; but not very much of a bend was needed. The procedure did work a little, and the two images ultimately almost converged. At least it was felt that the majority of the light from the star could be contained within the small aperture of the eyepiece, and the photomultiplier would receive enough light to function properly.

The material condition of the rest of the telescope was pretty good, and only minor repairs or adjustments were required. The most significant of these were that the reach rod from the clock drive assembly to the right ascension drive required welding, and the teeth of the right ascension drive gear were worn with a lot of backlash. This was corrected, in part, by dressing the teeth with a small file.

5.2 The Electronic Components

The AC/DC motor generator with a voltage regulator provided with the kit was completely useless. The set had been cannibalized and many of the components were missing. This unit

was supposed to provide the DC voltages required for the photomultiplier tube, as well as 6 and 24 volts for operation of various lights and accessories. This led to the necessity of using batteries to provide the power for the photocell. The procedures used are discussed in chapter 3 and shown in the appendix.

The photomultiplier tube was examined and it was decided that, as it was probably ten years old, a new one should be purchased. This tube is the heart of the whole system and if it does not function properly, the occultations can not be recorded. The wiring to the socket of the photomultiplier tube was broken and was all replaced.

Next, the D. C. amplifiers were examined. Three amplifiers were received and only two were required for the system. This was fortunate because, again, one of the amplifiers had been partially cannibalized. All the tubes in each amplifier were carefully marked and then removed and tested. Of the fourteen tubes for each amplifier, all but three were found to be in satisfactory condition. These three were able to be replaced from the "spare" amplifier. One of the calibration meters on the amplifier was broken, and was replaced from the "spare" amplifier. Thus, it appeared that there were two amplifiers that could possibly work after calibration and balancing.

The first amplifier energized after replacing a fuse. The balancing procedures of the operating manual [Brush Electronic Company, ED 31202] were followed, but all voltages required at the various test points could not be obtained. The next amplifier was taken and it was found that the balance control potentiometer had to be replaced before the amplifier would energize. Again, the balancing procedures were followed, but satisfactory results could not be obtained.

This observer's background in electronics did not provide sufficient knowledge of trouble-shooting to isolate the problem areas, so assistance was sought from some graduate students in Electronic Engineering. They were very helpful and quite interested in my problems because they had never seen any equipment that was quite like this. All the circuitry was quite "old fashioned" to them and they were interested to see just what the capabilities of these amplifiers were. We went through all the steps in the manual for alignment and balancing, but were not able to get the specified voltages. The consensus was that most of the resisters and condensers were just so old that they were not performing according to their designed specifications. A few isolated components were replaced, but in order to get everything working properly, they felt a general rebuilding of the amplifiers would be necessary.

Finally, after several days' effort, the amplifiers were adjusted to the maximum capability that they would ever be able to achieve without this general rebuilding. They were able to amplify a test signal about 500 times without too much background noise. They were at least ready to try in the system.

The next unit that had to be worked on was the oscillograph. This instrument was tested with a step voltage divider and both galvanometers appeared to be in good condition. The chart drive motor needed some overhauling and lubrication but finally worked well. The fast speed was tested with one second time ticks for several minutes, and the chart drive rate was found to be constant at 123mm/sec over this period. This was two millimeters per second slower than the specifications, but would not affect the results of the recording. The ink pens were both corroded and stopped up. It was necessary to boil them in water, soak them in pen cleaner and finally pierce the hole with a fine wire before they would work.

5.3 The Timing System

The 1000 cycle band pass filter for the radio signal was not available and this did cause trouble in trying to record the one second pips. When there was background noise in the radio signal, the pips were not discernable. Furthermore, when the Binary

[illegible]

[illegible]

[illegible]

[illegible]

coded time signal of WWV was broadcast while the pips were being recorded, the oscillograph pen would become very erratic. It was necessary to stop radio recording of time signals during this one minute of every five of the broadcast, as the oscillations of the oscillograph pen would mask even the chronometer time ticks on the same channel.

5.4 Observation Attempts

After the above efforts to get the components all in working order were completed, the system was fully assembled and the attempts to get everything to work together commenced. At this point it was February, 1968, and an average of 10-15 hours a week had been put in on the equipment. During this time this observer had been attempting to record occultations by manually timing the event on a chronograph. The results of this effort will be discussed later. In February, there were only two occultations predicted of stars of seventh mangnitude or brighter. Both of these stars were fifth magnitude, but on the nights involved the weather conditions prevented observation of either one. In fact, the weather was so adverse the entire month, no attempt was made to set up the equipment.

In March, there were predicted eight occultations. Two disappearances were scheduled on the night of March 9th. In

preparation for these, the equipment was set up and energized the night before. It was decided during the month's absence from the equipment that I could check out the system by manually occulting the star with a piece of cardboard passed in front of the telescope. This was attempted. The first star, Z. C. 1008, was located and tracked. This star is a fifth magnitude star and the manual occulting technique produced no perceptible deflection of the oscillograph pen. The next attempt was to track Venus, which was visable, and try the manual occulting technique on this, the brightest object in the sky, next to the moon. The occulting of Venus did show a very slight movement on the oscillograph pen. Over the next few weeks the entire electronic system was rechecked and adjusted to its maximum capability.

On the 16th of April, there were predicted two occultations, two hours apart. The first a 1.2 magnitude star and the other of 6.2 magnitude. Again, the equipment was fully assembled the night before the occultations. Venus was again manually occulted with slight deflection noted. The 1.2 magnitude star was tracked and manually occulted and just the slightest deflection of the pen was observable if the point was marked with a pen. It was decided to try to record the occultation the next night, however, on looking at the moon, this observer realized that he had failed to check on

[illegible]

[illegible]

whether this was to be a disappearance or a reappearance. The moon was past full and the occultation would be a reappearance. Knowing that the chances of the system working on a reappearance were very poor, it was decided to try it anyway, as the reappearance procedures had to be examined.

The next night the attempt was unsuccessful. The background light of the moon was too bright and the star emergence could not be discerned.

During the month of May, several more attempts were made to record occultations, but none of them could be observed by the electronic system. Manual occultations were discernable on Jupiter (magnitude -1.3) and Saturn (magnitude 1.1). A few stars, all brighter than second magnitude, were also able to give slight deflections on the oscillograph.

5.5 Conclusions

The Telescope, and associated electronic equipment comprising the kit, can work to record occultations of bright stars. However, in order to record the occultation of the dimmer stars, considerable energy and funds are going to have to be expended. The mirror should be resilvered and the amplifiers must be rebuilt. Once this is done, the observation team must include at least one

member with a good background in electronics. The critical factor in the method of recording the occultations with a photo-electric cell is clearly seen to be the dependence on the electronic system's capability to "see" the star. In order to be able to make enough observations in a reasonable length of time, the instrument must be able to record at least a seventh magnitude star. This will require the equipment to be in the best of material condition initially, and the field team must be able to perform the fine adjustments that will be necessary almost continuously.

Over the entire period of work with the occultation telescope, this observer attempted to manually time the disappearing contact of the occultations. No attempt was made to record the emerging contacts as there is too much personal error in timing the sudden reappearance of the star. A log of the occultations observed was kept and the results are tabulated in the appendix. Summarizing the table, it can be seen that of 40 occultations predicted, only 8 were able to be recorded manually. It is assumed that if the telescope systems were working, the results of the photo-electric recording would not have been any better. The weather conditions caused all but three of the failures. These conditions consisted not only of rain and snow storms, but the aggravating partly cloudy sky, when a cloud would pass in front of the moon just at the wrong

time. The other position determining methods also have weather restrictions, but at least the observations can be done over the entire month. With occultations, the useable period of the month is very restricted. The moon's phases over the month limit observation of occultations to those nights when the moon can be seen high enough, after sunset or before sunrise, and yet far enough from being full, to have a useable dark limb. These conditions give only about seven days each for disappearances and reappearances. There must, as well, during these seven day periods, be a useable star being occulted.

The occultation telescope can be used in areas where the average weather conditions can be expected to permit observations on most nights. If the weather conditions of an area indicate that more than three months might be needed to collect sufficient observations for reduction, another method of position determination should be considered.

It is the opinion of this observer that the telescope and the electronic equipment under investigation could satisfactorily be used to obtain the time of the occultation to 0.01 second if the primary mirror were resilvered and the amplifiers were rebuilt or replaced. Whether or not the occultation observation method could achieve

the accuracy of the satellite methods, is still a subject for investigation. As the satellite methods of position determination are now well established, with high internal precision, the use of occultations in Geodesy is not anticipated until investigations into the relative accuracy and cost of the two methods are completed.

APPENDIX I

Machine print out of Occultations predicted for Columbus, Ohio
[H. M. Nautical Almanac Office]

LUNAR OCCULTATIONS 1968

VISIBLE AT COLUMBUS, OHIO

LONG. 83.033 W LAT. 40.000 N

DATE MTH	D	U.T. H	MIN	Z.C.	MAG	ELONG DEG	PH	P.A. DEG	A/M	B/M	NAME
1	4	0	54.0	3284	7.1	49	D	110	-1.6	-2.6	
1	6	17	02.2	4006	1.1		D	065	---	---	SATURN
1	6	18	04.1	4006	1.1		R	232	---	---	SATURN
1	9	6	09.1	325	7.4	107	D	135	---	---	
1	9	23	08.0	416	5.4	116	D	113	---	---	042 ARIE
1	10	4	29.2	432	5.9	117	D	132	---	---	045 ARIE
1	11	7	42.1	563	6.9	129	D	148	---	---	
1	12	1	42.4	683	7.3	139	D	103	-2.5	-0.2	
1	18	2	31.3	1479	6.3	210	R	269	-0.3	+1.4	107 LEON
1	25	11	13.1	2373	6.2	305	R	242	-2.3	+2.0	116 SCOR
2	7	1	03.3	480	5.2	96	D	042	-1.7	+1.7	061 ARIE
2	11	8	47.1	1088	5.6	145	D	119	+0.1	-1.7	047 GEMI
3	9	1	19.4	1008	5.0	110	D	116	-2.1	-1.5	049 AURI
3	9	6	57.7	1035	6.8	112	D	086	-0.1	-1.1	
3	10	8	01.4	1169	5.4	124	D	129	+0.4	-1.8	076 GEMI
3	11	1	05.1	1270	6.1	134	D	092	-2.0	+0.7	028 CANC
3	19	8	17.0	2269	5.4	244	R	323	-0.9	-0.6	031 SCOR
3	21	10	05.8	2609	VAR	271	D	168	---	---	031 SGTR
3	21	10	31.8	2609	VAR	271	R	206	---	---	031 SGTR
3	22	10	31.9	2788	6.2	284	R	280	-1.6	+0.7	183 SGTR
4	01	0	53.6	415	6.0	35	D	104	-0.2	-2.0	040 ARIE
4	02	2	13.0	524	6.6	46	D	055	-0.5	-0.3	
4	06	2	39.0	1093	6.4	91	D	131	-0.7	-2.5	
4	06	5	55.3	1108	6.9	92	D	115	+0.3	-1.6	
4	09	3	36.4	1462	7.4	127	D	119	-1.5	-1.5	
4	10	3	30.3	1576	5.3	140	D	137	-1.3	-1.7	053 LEON
4	16	4	50.3	2366	1.2	224	D	067	-1.6	+2.0	021 SCOR
4	16	5	35.2	2366	1.2	224	R	340	0.0	-0.9	021 SCOR
4	16	6	02.3	2373	6.2	225	D	031	---	---	116 SCOR
4	16	6	12.7	2373	6.2	225	R	014	---	---	116 SCOR
4	21	9	37.8	3178	6.2	291	R	175	---	---	143 CARP
5	03	2	55.7	1056	7.0	60	D	178	---	---	
5	08	5	30.9	1644	4.1	122	D	148	-0.4	-2.2	077 LEON
5	18	8	05.3	3130	5.5	260	R	281	-1.4	+1.0	033 CAPR
6	05	4	30.0	1712	3.8	103	D	178	0.0	-2.8	005 VIRG
6	06	2	59.7	1814	7.0	115	D	124	-1.4	-1.5	071 VIRG
6	10	2	05.3	2366	1.2	170	D	060	-2.2	+2.1	021 SCOR
6	10	2	46.8	2366	1.2	170	R	345	0.0	-1.3	021 SCOR
7	12	9	10.9	3164	4.7	209	R	163	---	---	039 CAPR
7	14	8	38.8	3421	5.1	234	R	264	-2.3	+0.6	092 AQAR
8	02	1	55.9	2099	7.0	93	D	038	---	---	
8	02	2	13.7	2099	7.0	93	R	011	---	---	
8	27	19	27.0	1925	1.2	47	D	196	---	---	067 VIRG
8	27	19	57.3	1925	1.2	47	R	243	---	---	067 VIRG

LUNAR OCCULTATIONS 1968

VISIBLE AT COLUMBUS, OHIO

DATE MTH D	U.T. H MIN	Z.C.	MAG	ELONG DEG	PH	P.A. DEG	A/M	B/M	NAME
9 05	1 43.5	3164	4.7	155	D	085	-1.6	+1.1	039 CAPR
9 09	10 05.6	136	6.3	207	R	178	-0.2	+3.7	171 PISC
9 12	6 29.1	472	5.0	240	R	221	-0.6	+2.4	058 ARIE
9 15	6 38.1	885	5.6	273	R	273	+0.2	+2.1	406 TAUR
9 25	23 51.8	2157	6.1	45	D	115	-1.1	-1.6	047 LIBR
9 27	0 20.7	2312	5.6	58	D	111	-1.4	-1.4	065 SCOR
9 30	2 28.1	2831	5.9	99	D	026	-0.4	+0.8	234 SGTR
10 03	4 46.6	3271	7.1	138	D	022	-0.5	+1.2	
10 10	6 54.7	560	3.8	220	D	035	-1.1	+2.8	027 TAUR
10 10	8 12.7	560	3.8	220	R	273	-2.5	-0.2	027 TAUR
10 10	8 09.3	561	5.2	220	R	294	-3.1	-1.8	028 TAUR
10 10	7 17.7	564	6.1	220	D	142	---	---	
10 10	7 36.2	564	6.1	220	R	166	---	---	
10 19	11 27.9	4005	-1.3		D	115	---	---	JUPITER
10 19	12 39.5	4005	-1.3		R	315	---	---	JUPITER
10 31	4 54.8	3355	6.8	120	D	359	+0.4	+2.6	243 AQAR
11 02	5 17.2	50	6.0	144	D	088	-2.0	-1.0	044 PISC
11 07	6 39.1	647	5.5	201	R	213	-1.5	+3.0	059 TAUR
11 08	10 30.1	797	6.3	213	R	293	-1.2	-2.2	354 TAUR
11 11	9 20.1	1206	5.9	246	R	291	-2.1	-0.7	002 CANC
11 11	9 46.5	1211	6.2	246	R	229	---	---	004 CANC
11 15	9 48.6	1644	4.1	293	D	092	-1.3	+1.3	077 LEON
11 15	10 49.7	1644	4.1	293	R	338	-0.8	-1.8	077 LEON
11 25	1 29.7	3037	7.3	63	D	005	+0.7	+1.9	073 CAPR
11 30	5 40.9	132	6.9	126	D	042	-0.8	+0.6	169 PISC
12 02	7 06.0	371	6.4	149	D	034	-1.1	+1.1	027 ARIE
12 08	8 10.4	1169	5.4	215	R	234	---	---	076 GEMI
12 11	10 04.3	1504	5.7	250	R	356	-0.3	-3.7	037 LEON
12 13	9 44.6	1712	3.8	274	D	073	-2.7	+2.4	005 VIRG
12 15	10 26.8	1712	3.8	274	R	006	+0.3	-3.6	005 VIRG
12 25	0 49.7	3391	6.8	70	D	335	+0.5	+3.0	085 AQAR
12 25	1 41.8	3394	7.4	70	D	358	+0.4	+2.7	087 AQAR
12 28	2 08.1	209	7.2	106	D	067	-1.8	+0.3	254 PISC
12 31	1 03.1	545	4.2	139	D	014	-0.2	+4.0	023 TAUR
12 31	1 13.5	550	6.8	139	D	074	-1.8	+1.4	
12 31	1 24.1	551	7.1	139	D	052	-1.4	+2.1	
12 31	2 01.1	552	3.0	139	D	006	---	---	025 TAUR
12 31	2 48.4	552	3.0	139	R	304	---	---	025 TAUR
12 31	2 38.6	560	3.8	140	D	064	-2.0	+1.2	027 TAUR
12 31	2 48.2	561	5.2	140	D	047	-1.8	+2.0	028 TAUR
12 31	7 59.4	587	6.4	142	D	077	-0.5	-0.9	

[illegible]

APPENDIX II

Prediction procedures for time of contact using the method of the Explanatory Supplement to the Ephemeris, Chapter 10B.

The method of prediction of the contact time given in the Explanatory Supplement to the Astronomical Ephemeris and the American Ephemeris and Nautical Almanac, is presented herein. It is itself, not very complicated, but the reader is forced to turn to several different sections, to get the necessary formulae. A sample problem has been worked for an occultation observed at Columbus, Ohio, to demonstrate the method.

The problem, is that of finding the time at which the projection of the observer's position on the fundamental plane, lies on a circle of constant radius (k), and whose center (x, y) is the projection of the moon's center. This constant radius, is the moon's radius; the value adopted for k, is 0.2725026. If ξ and η are the coordinates of the observer's projection on the fundamental plane, the condition for a disappearance or reappearance is:

$$(x - \xi)^2 + (y - \eta)^2 - k^2 = 0.$$

This condition will not be satisfied in general, by the selection of the time interval from the time of conjunction, and the method is used to find a more accurate time.

The basic data used for each prediction consist of:

<u>Besselian elements at the time of conjunction</u>

T_0 = The U. T. of conjunction in right ascension.

H = The Greenwich hour angle of the star at T_0.

Y = y at T_0.

x', y' = The hourly variations of x and y.

$\alpha*$, $\delta*$ = The right ascension and declination of the star.

<u>Geocentric coordinates of the observer</u>

λ = The geocentric longitude.

ρ = The geocentric radius vector to the observer.

φ' = The geocentric latitude.

Occultation Prediction (η Leonis)

1. Conjunction of moon and star. (T_0)

Preliminary predicted time		$0^h 24^m 24^s$
20 April 1967		13 49 34
		0 03.9
		0.1
	$G\varphi$	14 14 02
	α	10 06
	GHA	$4^h 08^m$

Star Coordinates: η Leonis

$$n = (0 + 4\text{-}08/24) = 0.0172$$

$\alpha = 10^h 05^m 33^s.158$	$\delta = 16^\circ 55' 27''.65$
$+n\ (-\ .119)$	$+n\ (+\ .69)$
0	0
10 05 33.156	16 55 27.66
.0107	−.038
$\alpha* = 10^h 05^m 33^s.167$	$\delta* = 16^\circ 55' 27''.62$

Moon Coordinates:

Center of disk correction $\Delta\beta = -\ 0''.6$

$$\Delta\alpha = -\ \sin\epsilon\ \cos\lambda\ \sec^2\delta\ \Delta\beta$$

$$\Delta\delta = (\cos\epsilon\cos\lambda\ \cos\alpha\ + \sin\lambda\ \sin\alpha)\,\Delta\beta$$

At 20 IV:

$\lambda = 146^\circ 35' 36''$	
$\alpha = 10^h 02^m 23^s$	$\Delta\alpha = 0^s.015$
$\delta = 17^\circ 19' 56''$	$\Delta\delta = -\ 0''.56$
$\epsilon = 23^\circ 26'$	

Right ascension of the Moon tables from AENA plus center correction.

IV - 20 - 0	$10^h 02^m 23^s.320$		
		+ 137.704	
1	10 04 41.024		−.162
		+ 137.542	
2	10 06 58.566		−.160
		+ 137.382	
3	10 09 15.948		

Solve for interpolating factor n.

$$10^h 05^m 33^s.167 = 10^h 04^m 41^s.024 + n(137^s.542) + {}^1/_4(n)(n-1)(0^s.322)$$

$0.0805\,n^2 + 137.4615\,n - 52.143 = 0$

$n = 0.3795$

Using this interpolating factor in tables above we get

$\alpha_M = 10^h 05^m 33^s.202$

$$\delta n = \frac{(33.202 - 33.167)}{137.542} = 0.0002$$

$n = 0.3795 - 0.0002 = 0.3793$.

Using this new n, in the table by inverse interolation we get the time of geocentric conjunction in right ascension.

T_E = IV $20^d\, 01^h\, 22^m\, 45^s.48$ (Ephemeris time)

T_U = IV $20^d\, 01^h\, 22^m\, 09^s.48$ (U. T.)

2. Computation of the Besselian elements.

$T_O = T_U =$	$01^h\, 22^m\, 09^s.48$
	13 49 34.238
	13.471
	.026
G. S. T.	15 11 57.215
α*	10 05 33.167
H =	$05^h\, 06^m\, 24^s.048$

Declination and parallax of the Moon.

From the tables in theAENA with the center of mass correction added:

Declination

IV - 20 - 0	17° 19′ 55″.89		
		- 806.06	
1	17 06 29.83		+ 6.81
		- 812.87	
2	16 52 56.96		+ 6.74
		- 819.61	
3	16 39 17.35		

Parallax

IV - 19.5	58′ 55″.580		
		+ 25.679	
20.0	59 21.259		- 1.051
		+ 24.628	
20.5	59 45.887		- 1.685
		+ 22.943	
21.0	60 08.830		

$$n_{\pi} = (1 + 0.3793)/12 = 0.11494$$

$$\Pi_M = 59'21''.259 + (.11494)(24''.628) + (-.0254)(-2''.736) = 59'24''.159$$

$$\Pi_M = 3564''.159$$

$$\delta_M = 17^\circ 06'29''.83 + (.3793)(-812''.87) + (-.0589)(13''.55) = 17^\circ 01'20''.71$$

$$\begin{aligned} \delta_M &= 17^\circ 01'20''.71 \\ \delta^* &= \underline{16\ 55\ 27.62} \\ \Delta\delta &= \quad 05'53''.09 = 353''.09 \end{aligned}$$

The coordinates of the center of the Moon on the fundamental plane are given by:

$$x = \frac{\cos\delta_M \sin(\alpha_M - \alpha^*)}{\sin \Pi_M}$$

$$y = \frac{\sin\delta_M \cos\delta^* - \cos\delta_M \sin\delta^* \cos(\alpha_M - \alpha^*)}{\sin \Pi_M}$$

As the angles are small, we use the approximations at T_0 that:

$$\sin(\alpha_M - \alpha^*) = 0\ ,\ \cos(\alpha_M - \alpha^*) = 1\ ,\ \text{and } \sin \Pi_M = \Pi_M.$$

With these approximations, the above formula for the coordinates of the center of the Moon reduce to:

$$x = 0$$

$$y = Y = \frac{\delta_M - \delta^*}{\Pi_M}$$

Substituting in our values, we obtain:

$$Y = \frac{353''.09}{3564''.159} = 0.09907$$

The derivitives of the Moon's center formula can be approximated as:

$$x' = \frac{15\cos\delta_M \alpha'_M}{\Pi_M}$$

$$y' = \frac{\delta'_M}{\Pi_M} - \frac{Y\Pi'_M}{\Pi_M}$$

where α'_M , δ'_M , and Π'_M are the hourly rate of change and are determined by interpolation of the first differences in the AENA tables and devided by 12.

$$\alpha'_M = 137.542 + \tfrac{1}{2}(0.3793)(-0.322) - \tfrac{1}{4}(-0.322) = 137.561$$

$$\delta'_M = -812.87 + \tfrac{1}{2}(0.3793)(13.55) - \tfrac{1}{4}(13.55) = -813.69$$

$$\Pi'_M = 24.628 + \tfrac{1}{2}(0.11494)(-2.736) - \tfrac{1}{4}(-2.736) = 25.155$$

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Substituting these values into the derivitive formulas we get:

$$x' = 0.55357$$

$$y' = -0.22899$$

Thus the Besselian elements of the occultation are:

$$T_0 = 1967 \text{ IV } 20 - 01^h 22^m 09^s.48 \quad (\text{U.T.})$$

$$H = 05^h 06^m 24^s.048$$

$$Y = 0.09907$$

$$x' = 0.55357$$

$$y' = -0.22899$$

$$\alpha * = 10^h 05^m 33^s.167$$

$$\delta * = 16^\circ 55' 27''.62$$

3. Geocentric coordinates of the observer.

Assumed geodetic coordinates of the observer:

$$\varphi = 40^\circ 00' 28''.0 \quad \text{N.}$$

$$\lambda = 05^h 32^m 09^s.45 = 83^\circ 02' 21''.75 \quad \text{W.}$$

$$h = 245 \text{ m.}$$

The geocentric rectangular coordinates are computed from:

$$u = (N + h) \cos\varphi \cos\lambda$$

$$v = (N + h) \cos\varphi \sin\lambda$$

$$w = [N(1 - e^2) + h]\sin\varphi$$

where λ is East geographic longitude

φ the geographical latitude

h is the hieght about sea level

$N = a/(1-e^2\sin^2\varphi)^{\frac{1}{2}}$

a is the equatorial radius of the earth

e is the eccentricity of the earth ellipsoid

After performing the above calculations we obtain:

$$u = 0.09295789$$

$$v = 0.76140677$$

$$w = 0.63945982$$

Next we compute the values:

$$\rho\sin\varphi' = w = 0.63945982$$

$$\rho\cos\varphi' = \sqrt{u^2 + v^2} = 0.76706026$$

$$H - \lambda = 23^h 34^m 14\overset{s}{.}598$$

$$\sin(H - \lambda) = -0.1121484$$

$$\cos(H - \lambda) = 0.9936915$$

The rate of change of the sidereal hour angle (h') is:

$$h' = \frac{(2\pi)(1.002738)}{24} = 0.262516 \text{ rads/hr}$$

4. The iterative solution.

The table on the next page gives the mathematical steps in the left column for each stage of the iteration. In this problem the iterations converge on the fourth series. The final Δt is $-0^h 57^m 49\overset{s}{.}24$. This gives the local time of the occultation as $19^h 24^m 20\overset{s}{.}24$ on the 19th of April 1967.

5. The position angle.

The position angle is found from the formulas:

$$\sin P = -f/k \qquad \cos P = -g/k$$

care must be taken to watch the signs of the above in order to determine the quadrant of the position angle. For our problem:

$$P = 71\overset{\circ}{.}9$$

Iterative Solution of Contact Time

$\Delta t =$	$\Sigma\,\delta t$	0	$-.^{h}98762$	$-.^{h}96373$	$-.^{h}96367$
$x =$	$x'\Delta t$	0	-.54671	-.533492	-.533459
$y =$	$Y + y'\Delta t$	+.09907	+.32523	+.319755	+.319741
$h =$	$H - \lambda + 1.0027\Delta t$	$23^{h}34^{m}14^{s}.6$	$22^{h}34^{m}49^{s}.6$	$22^{h}36^{m}15^{s}.8$	$22^{h}36^{m}16^{s}.0$
$\sin h =$		-.112148	-.363143	-.357295	-.3572814
$\cos h =$		+.993692	+.931734	+.933992	+.9339968
$\xi =$	$\rho\cos\varphi'\sin h$	-.08602	-.27855	-.274067	-.274056
$Q =$	$\rho\cos\varphi'\cos h$	+.76222	+.71470	+.716428	+.716432
$R =$	$\rho\cos\varphi'\cos\delta^*$	+.611765	+.611765	+.611765	+.611765
$\eta =$	$R - Q\sin\delta^*$	+.38987	+.40371	+.403206	+.403205
$f =$	$x - \xi$	+.08602	-.26816	-.259425	-.259403
$g =$	$y - \eta$	-.29080	-.07848	-.083451	-.083464
$f' =$	$x' - h'Q$	+.353475	+.36595	+.365496	+.365495
$g' =$	$y' - h'\xi\sin\delta^*$	-.22243	-.20770	-.20805	-.208046
$-B =$	$-2(ff' + gg')$	-.19018	+.16367	+.154914	+.154892
$B^2 =$		+.03617	+.02679	+.023998	+.023992
$A =$	$f'^2 + g'^2$	+.17442	+.17706	+.176872	+.1768697
$2A =$		+.34884	+.35412	+.353744	+.3537394
$4C =$	$4(f^2 + g^2 - k^2)$	+.07083	+.01525	+.000037	-.000006
$D =$	$B^2 - 4AC$	+.02382	+.02409	+.023992	+.0239926
$\sqrt{D} =$		+.15434	+.15521	+.154893	+.1548956
$\delta t =$	$-B - \sqrt{D}/2A$	$-.^{h}98762$	$+.^{h}02389$	$+.^{h}000059$	$-.^{h}0000094$

Δt (final) = $-.^{h}963679 = -0^{h}\ 57^{m}\ 49^{s}.24$

$T_{CCT} = 01^{h}\ 22^{m}\ 09^{s}.48 - 0^{h}\ 57^{m}\ 49^{s}.24 = 0^{h}\ 24^{m}\ 20^{s}.24$ (20 April) U. T.

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APPENDIX III

Power Supplies for the 1P21 Photomultiplier Tube

The 1P21 Photomultiplier tube requires 900 volts of direct current in ten steps of 90 volts each. This may be provided by two methods. The preferred method would be constructing a full-wave rectifer with voltage divider. This would provide constant voltage and can be regulated very precisely. The second method, and the one used by this observer, is a simple connection of 90 volt batteries with taps off for the various dynodes of the 1P21 tube.

Both methods are illustrated with circuit diagrams on the following page. The battery system, Figure A1, is very simple and no further explanation is needed. The rectifier system is more complicated and the notation used in Figure A2 is explained here.

C 1, C 2: 2 microfarad, 1000 volts condensers.

L 1, L 2: United Transformer Corp. No. R-17 or equivalent.

R: 200000 ohms, 12 watts, variable resistor.

T 1: United Transformer Corp. No. S-45 or equivalent.

T 2: United Transformer Corp. No. FT-6 or equivalent.

Voltage Divider: 10 resisters, each 20000 ohms, 1 watt.

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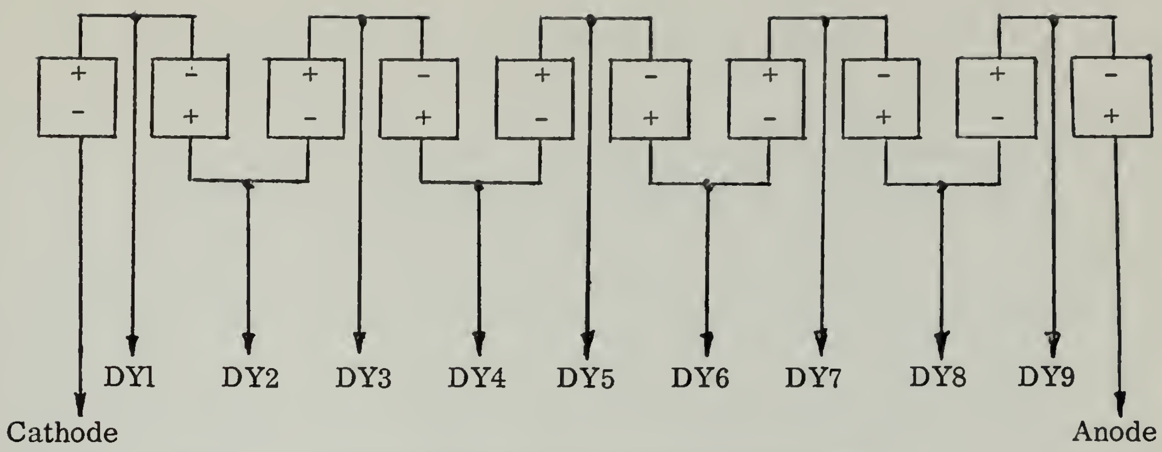

Figure A1 - Wiring diagram for 90 volt batteries

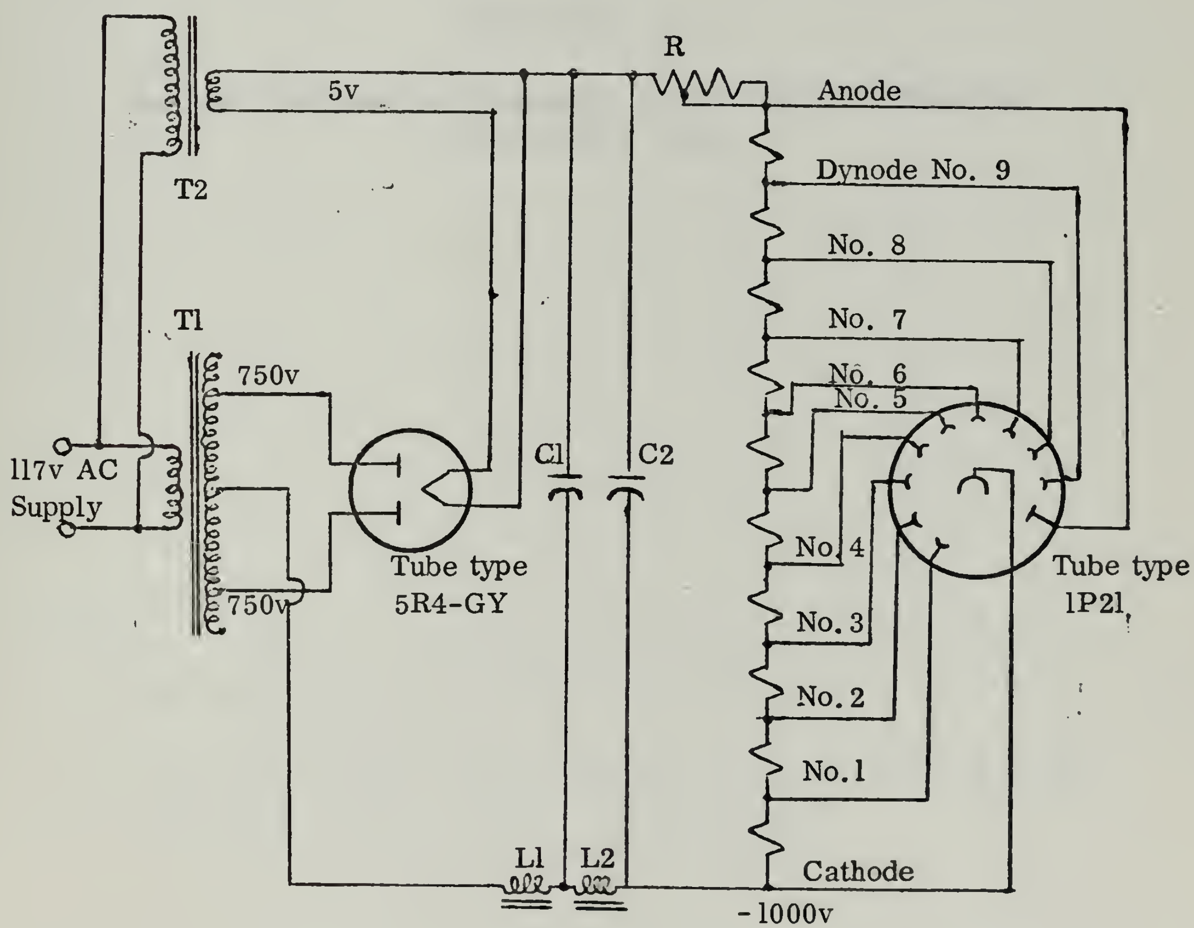

Figure A2 - Full-Wave Rectifier Power-Supply Circuit

APPENDIX IV

Log of Disappearing Contacts of Occultations observed at Columbus, Ohio

APPENDIX IV

Log of Disappearing Contacts of Occultations observed at Columbus, Ohio

OCCULTATIONS AT COLUMBUS, OHIO

Month	Number Predicted	Number Observed	Reasons for Non-Observence Radio Failure	Weather	Other
Oct 67	5	1	1	2	1 *
Nov 67	6	1		5	
Dec 67	4	0		4	
Jan 68	7	2	2	2	1 **
Feb 68	2	0		2	
Mar 68	4	0		4	
Apr 68	6	2		4	
May 68	2	0		1	1 ***
Jun 68	3	2		1	
Jul 68	1	0		1	
Totals	40	8	3	26	3

Notes:

* Miscalculation of local date.

** One of occultations was of Saturn, but occurred in daylight.

*** Chronograph spring drive motor ran down.

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